V. Finkel

The Portrait of a Crack

Mir Publishers Moscow

V. Finkel Dost 1.5

The Portrait of a Crack

В. М. Финкель

Портрет трещины

Издательство «Металлургия» · Москва

V. Finkel

The Portrait of a Crack

Translated from the Russian
by Y. Nadler

Mir Publishers
Moscow

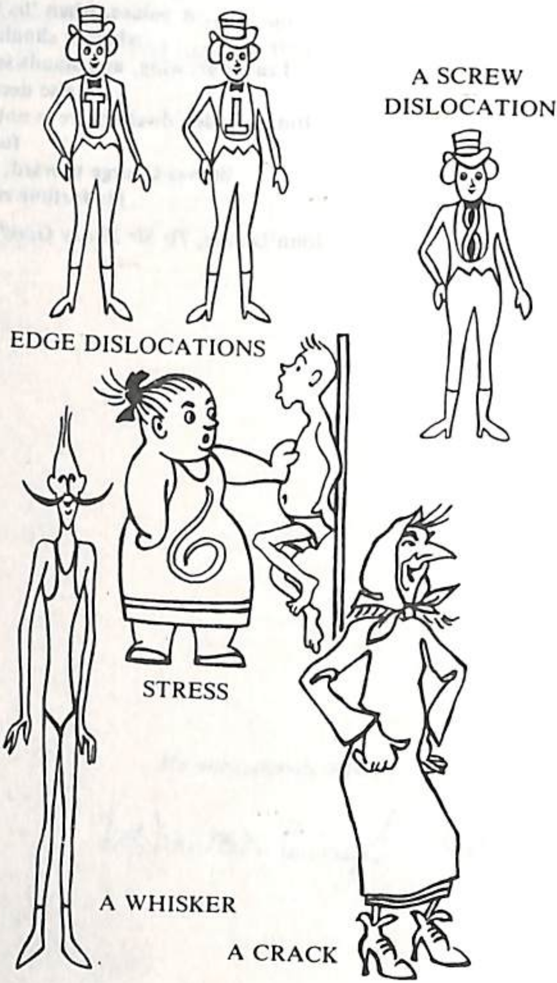
First published 1985
Revised from the 1981 Russian edition

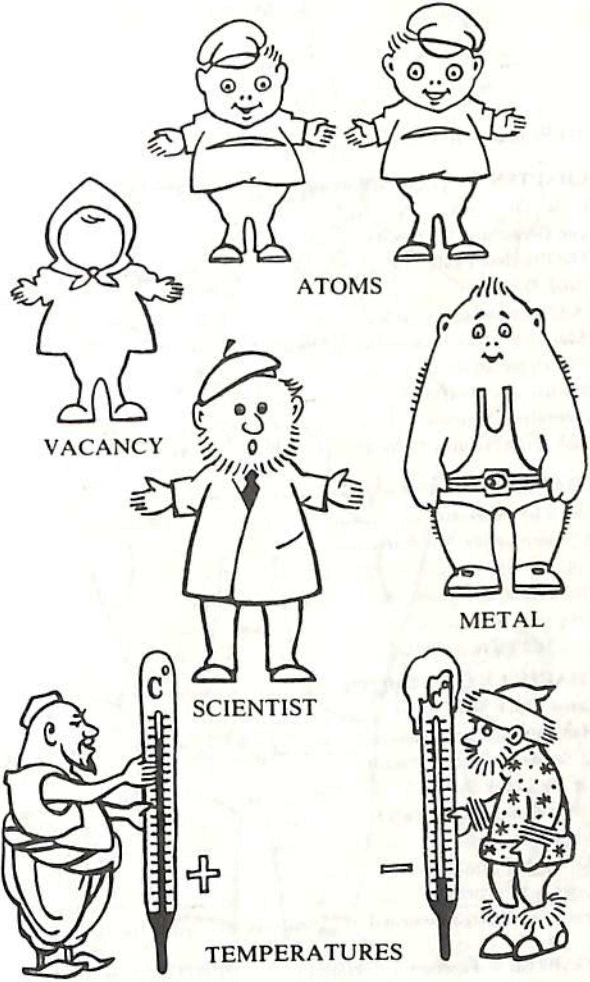
На английском языке

Ishwar Singh Dost

A palace, when 'tis that
which it should be
Leaves growing, and stands such,
or else decays;
But he which dwells there is not so,
for he
Strives to urge upward, and
his fortune raise.

John Donne, *To Sir Henry Goodyere*


A SCREW DISLOCATION
EDGE DISLOCATIONS
STRESS
A WHISKER
A CRACK


ATOMS
VACANCY
METAL
SCIENTIST
TEMPERATURES
C°
+
C°
−

Contents


300 kN!
960 km/h

TO PRAISE OR TO CONDEMN?

To approach is the beginning of knowledge.

(After J. Cortázar)

That was the question that confronted the author when he first thought of writing this book. Of course, fracture and its implement, a crack, are, as a rule, a misfortune and, in the event of casualties involving the loss of life, a tragedy.

But in order to write, the author had to be inspired by something. By what?

There is nothing esthetic about fracture. Yet it cannot be fought without knowing its laws. It is often quite sensational. How else, for instance, can you characterize the collision of an airplane and a bird? The force of impact of a dove against a plane when its speed is only 320 km/h amounts to 32 kN; and when its speed is 960 km/h, almost 300 kN. The fracture that ensues is indeed serious.

Sensations, however, evoke different and at times quite contradictory emotions and may prevent the reader from interpreting facts and events objectively. No, I doubt whether I can base a book about fracture on sensations.

After all, the most suitable approach, from my point of view, is the one prompted by the following words of a Moscow radio announcer: "Stay tuned for our next broadcast: *Health. Diabetes Mellitus.*" As a matter of fact, destruction is the negative side of strength. And if it is absurd to sing the praises of a shadow, is there any reason why we should not be enraptured by the delicacy and strength of a television tower, the lightness of a bridge spanning a strait many kilometers long or the exquisite grace of a hundred-meter space rocket? All this is dealt with in one of the branches of modern solid-state physics which gives the basis for the conceptions of the great strength of materials, their ability to resist the adverse effects of high and low temperatures, corrosive media, pulse loads and the inconceivably large number of other factors that act on modern structures. Whether we speak of a chemical or nuclear reactor, the frame of a supersonic airplane or rocket, an oil drill or ice-breaker, the main question is always — how long will it last? Will no disastrous fracture occur? How can a machine, device or

apparatus not only be made as light and cheap as possible but thoroughly safe as well?

It is precisely solid-state physics with its various fields and trends that is capable of providing contemporary civilization with the main structural materials. The well-known English physicist J. J. Thomson once said that in technological progress there are three basic elements: knowledge, energy and materials. That is why approximately one third of the physicists all over the world are now working on finding new metals and metal alloys as well as a wider application of old ones. There are very good grounds for this. It is sufficient to say that almost all the tools created by man are made of metal. Moreover, all that is most responsible, safe and reliable on earth is made of metal: be it a bridge across a large river, the pincers and scalpel of a surgeon or the chamber of an accelerator of nuclear particles. It is namely metal structures that obstructed the powerful landslide and saved the city of Alma-Ata in the Soviet Union. Gigantic reinforced-concrete dams span great rivers to give us electric power.

Still, in modern science, among the multitude of problems concerned with strength, fracture occupies a special place. When we hear of an accident befalling a passenger airplane involving many victims (a wing fell off) or of a submarine being crushed by a layer of water many kilometers thick, or of the appearance of fractures in the housing of a nuclear reactor (possibly polluting the environment and exposing people to radiation), it becomes especially clear that measures must be immediately taken to prevent the reoccurrence of such calamities. But what measures?

We remember a newspaper report: cracks were detected in the fins of *Saturn*, rocket which was to launch the American spaceship in the joint Soviet-American *Soyuz-Apollo* flight, and all eight fins had to immediately be replaced by new ones. This caused no delay in launching; but it can be otherwise when, for instance, the propeller blade of a helicopter breaks during flight and the machine falls down like a stone. Or when an oil or gas pipeline explodes due to the propagation of a crack along a distance of 10-20 km at a full speed of 1 000-2 000 m/s.

The damage is always very great and cannot be remedied in the event of a loss of life. . .

It is said that the atmosphere in which a specialist works does not always act beneficially on him. That is why criminal investigators

who have to learn thieves' cant try not to become infected by it; psychiatrists have to counteract the madness of their patients by means of their own bright intelligence and boundless optimism. It can be supposed that something like that happens to a scientist whose field of study and research is fracture. To one who has fathomed many of its mysteries it might seem that disastrous fracture is all-powerful, while reliable strength does not exist at all. . . Fortunately, this is not the case. On the contrary, the scientist is convinced that not only can adequate strength be ensured, but fracture itself, no matter how paradoxical it may seem, can be useful to man.

It suffices to point out that throughout the world, on a gigantic scale, the mining of minerals, in particular coal and various ores, is based on fracture. The machining of metals on metal-cutting lathes also involves complex fracture as do the technological processes of cutting granite and marble.

In Nature we encounter quite often the interruption of continuity. Thus, a lizard when fleeing from its foe sacrifices its tail to save its life. A spider-synoptic when foreboding a strong wind destroys its own web. The roots of trees fracture rocks. Mushrooms that seem so frail at a first glance, thicken and are capable of breaking through asphalt and boring through thick cement-like layers of termites in the tropics. Beans on swelling with moisture have been known to rupture the holds of tankers. It is affirmed that in ancient times, the first anatomists used beans to separate the bones of a skull.

The book lying in front of you is dedicated to fracture, its nature and its manifold manifestations: when it is a naked evil and when it is vitally important and successfully serves man. In both instances, however, the author strove to be optimistic, never forgetting that each case of fracture demands a particular approach and definite action. Perhaps it would not be bad if Nature were simpler than it is, but how good it is that there is yet much that is still unknown, even fraught with danger, to which we can devote our courage, our intellect and our hands. Not the least part in this is played by that amazing human trait — the eagerness to learn and know, one of the most astonishing and unselfish key factors of human thinking and creating. The American writer Kurt Vonnegut expressed this thought very well through the words uttered by a scientist in his speech when he accepted the Nobel Prize: "Ladies and gentlemen, I stand before you now because I never stopped

dawdling like an eight-year old on a spring morning on his way to school. Anything can make me stop and look and wonder and sometimes learn. I am a very happy man."[1]

This book is intended for inquisitive readers; the author tried to write it in such a way that it would be interesting and instructive for school boys and girls as well as for engineers.

It is for the reader to judge whether the author has succeeded in achieving this.

---

[1] Kurt Vonnegut, Jr., *The Cat's Cradle*, New York, 1963, p. 20.

Strength in itself is a blessing.

(After Honoré de Balzac)

Chapter 1
A Crack Without a Dress-Coat and Tie

INITIAL DIAGNOSIS

> **Tearing squares of shining cellophane.**
> **Some easily, some in evident torment tore,**
> **Some for a time resisted, and then burst.**
> John Berryman, *1 September 1939*

The impressive equestrian statue of Peter the Great in Leningrad — the world famous 'Bronze Horseman' — has witnessed an amazing flow of events. It seems not only to rise above the waves of the Neva but also above time, independent of it. However, nothing can withstand time, and cracks have appeared in the statue. What has happened to Falconet's sculpture? There are several answers to this question. The simplest one is based on the age-old laws of mechanics and can be expressed approximately as follows: it is the result of overload; the entire weight of the eight-ton monument presses on the hind legs and tail of the horse. This is all the more so because under the action of winds the horse seems to sway from one foot to another. The second answer is more penetrating: it is due to fatigue of the metal which is subjected to corrosion — on the outside the statue is surrounded by the usually humid atmosphere and inside, through cracks in the body, it is filled with tons of accumulated rain water. Corrosion promoted fracture under the action of considerable mechanical loads.

In this narrative we are interested in the first approach to the causes of fracture which is a phenomenon as old as civilization. At the beginning it attacked man's primitive dwellings and stone axes; later, his wooden houses, bridges and caravels (sailing vessels).

This is how Thornton Wilder describes the breaking of an ancient bridge: "On Friday noon, July the twentieth, 1714, the finest bridge in all Peru broke and precipitated five travellers into the gulf below. This bridge was on the highroad between Lima and Cuzco and hundreds of persons passed over it every day. It had been woven of osier by the Incas more than a century before and visitors to the city were always led out to see it. It was a mere ladder of thin slats swung out over the gorge, with hand rails of dried vine. Horses and coaches and chairs had to go down hundreds of feet below and pass over the narrow torrent on rafts, but no one not even the Viceroy, not the Archbishop of Lima, had descended with the bag-

gage rather than cross by the famous bridge of San Luis Rey. St. Louis of France himself protected it, by his name and by the little mud church on the further side. The bridge seemed to be among the things that last forever; it was unthinkable that it should break . . ."[1]

There is nothing surprising in the fact that the Incas knew nothing of mechanical strength, of the laws of mechanics. But we know that long before this event, at the end of the XV and the beginning of the XVI century, the great Leonardo da Vinci already made use of calculations of wooden structures; spoke of minute particles of the wood that were broken under the effect of variable load, of the penetration of 'spaces' into the material, which drew them further apart and led to the appearance of 'cavities', i.e., cracks, according to modern conceptions. Moreover, da Vinci knew very well the dangerous spots in a structure, which he considered to be, for instance, keyed, grooved, and other joints. He believed that the most dangerous places in these joints were the 'dead ends' where the contact surfaces of adjacent planes altered their direction. Thus Leonardo da Vinci came to understand one of the most important concepts of modern mechanics of strength — the concept of concentration and concentrators of stress. Hence, the great thinker and scientist laid the foundation for the modern concept of the mechanism of fracture. This is all the more amazing since we are talking about the middle ages, a time when the limited knowledge of man and his helplessness before the forces of Nature made him accept a fatalistic view of the world he lived in.

Just what is stress concentration? Suppose we have to solve the following problem: we want to cut a sheet of rubber. There are many ways of doing it. We can, for example, cut it with a pair of scissors. But what if the rubber is too thick? Then we will hardly succeed in cutting it. Let us try to use a knife for this purpose; but we could damage the surface of the table when doing so. There is a simpler way — let us bend the sheet of rubber and cut it slightly with a razor blade; a slit will immediately appear and quickly open up. One more movement of the blade and the place where the rubber is bent will open along the entire cross section. What has happened? When we bent the rubber we deformed it and the stress field was 'driven in'. This field tends to straighten out the rubber and

---

[1] Thornton, Wilder, *The Bridge of San Luis Rey*, London, 1962, p. 1.

disappear. It is here that the razor blade comes to its aid: at first it makes a small incision, a stress concentrator, that concentrates all the energy of elastic deformation in a very small part of the material. When you come to think of it, that is just how the enemy's front is broken through in a narrow battle zone where superior forces are gathered by drawing up troops from other areas. And directly after the front is broken through. . . the main mass of forces rushes in. A stress concentrator is the seat of fracture. It is of interest that the 'better' the concentrator, i.e., the sharper it is, the sooner breaking takes place; in other words, the 'worse' it is for a given structure. This makes sense, at least verbally, since we have decided not to make use of formulas and mathematical calculations.

Henceforth, however, we should keep in mind that as the sharpness of the incision increases, the stress at its apex increases rapidly, inversely proportional to the square root of the radius of the cut. That means that if it is one tenth of a centimeter, the stress in it will increase approximately three times. And if it is as small as one ten-thousandth fraction of a centimeter, the stress in the metal will increase a hundred times. It might seem that fracture would set in at once. But, fortunately, Nature has taken care of that, by imparting to a large number of important materials a 'safety' mechanism, namely, plastic deformation. It is precisely plastic deformation rather than fracture that first occurs in a very sharp cut in steel. Recall what happens when you want to break a copper wire. On bending it back and forth many times you notice that a crack finally appears and fracture takes place. This process can be speeded up if the wire is preliminarily notched. Just the same in copper, aluminium and low-carbon steel, some bending and plastic deformation is needed. The degree to which this is necessary, depending on the material (let's say, in marble or in butter brought in from the frost) varies greatly; but the phenomenon is almost always there. Nevertheless, all is not as simple as it may seem and various points of view are possible. According to one of them, plastic deformation is not essential for fracture; in its absence a structure will break anyway. And it should be pointed out that although there are not very many who support this point of view, it rests upon the laws of fracture of truly brittle materials such as glass and is also quite convincing.

But we will return to this question later.

Meanwhile, in order to appraise the different points of view that exist on this phenomenon, a little more reasoning is needed and only armed with a thin reliable scalpel will we be able to understand how to convert the apex of a cut into a crack, either avoiding or making use of plastic deformation.

Let us turn our attention to the essence of the purely mechanical approach to fracture.

Is it so necessary to make a great distinction between a stress concentrator and a crack? Ultimately, they differ only in that in a stress concentrator the apex is relatively obtuse whereas in a crack it is inconceivably sharp, hundred-millionths of a centimeter, i.e., a magnitude of the order of an interatomic spacing. Hence, from the point of view of mechanics only the degree of stress concentration differs, but not the essence of the process. Therefore it is not at all necessary to analyze the origin of an initial microcrack at the bottom of a cut in detail, at the level of behavior of individual atoms.

Well, how about the part played by plastic deformation in this approach? The answer is very simple: there is no need to dramatize! Yes, of course, plastic deformation exists; yes, it precedes fracture. What role does it play? That of devourer of energy imparted to a body by an external load. If there is no fracture, all the energy is spent on deformation. If fracture has already set in, only part of the external energy is spent on its growth; the rest on deformation. In the second case, fracture takes place accompanied by plastic flow, just as the sound of a musical instrument is softened by means of a mute.

There are many flaws in this approach. In fact, it does not answer the age-old questions of why and how the concentrator was converted into a crack, how plastic deformation is connected with fracture, what is the structure of a material in the zone where a crack has originated is and many others. Still this approach possesses unique merits. It enables us to calculate actual cases of fracture just because it ignores the fine structural details which are always difficult to estimate quantitatively. It is obvious that it is much easier to calculate any mechanism than the complicated processes that take place at the atomic level.

Perhaps the best example of such an approach to evaluating the strength of a material is the theory proposed by A. Griffith, an English engineer, subsequently an aircraft designer. He noticed that the real strength of a structure is always less than expected of it. He explained this as follows: no matter how monolithic a metal may

outwardly seem to be, it contains cracks. Where did they come from? What is their nature? Griffith did not find the answers to these questions and most likely he did not even look for them. The answers came later, 30-40 years afterwards, and they were found by other investigators. But Griffith was right in the most important thing, which was later repeatedly confirmed by many physicists: metals do actually contain cracks of all sizes that are often very dangerous. These cracks grow in the same way diseases progress, reducing the life span of machine parts which are thus doomed to premature failure.

What is the mechanism of the effect of cracks on strength?

Ultimately, it all comes down to stress concentration. Let us suppose that there is a large crack in a piece of metal. It naturally reduces the section of the material that resists the applied load and the stresses that act on the rest of the material are accordingly great. It is, however, not always as simple as that. Even if a metal plate were infinitely large, just the same, stresses would accumulate at the crack's tip exceeding the average stress several times, sometimes, as we have already pointed out, by several orders. This occurs in a volume of the metal approximately the size of the crack itself. The area in which the stresses accumulate has an interesting shape — something like 'ears' on both sides of the tip of the crack. In these 'ears' considerable elastic energy is collected which tends to rupture the metal. A crack in metal under stress always has 'ears' and it can even 'flap' them when the conditions of propagation vary or when the crack is situated at the boundary between two different layers of a composite material. This indicates a change in the distribution of stresses in the vicinity of the tip of the crack. The reader now knows more about these 'ears' than Griffith knew in his time. Such a distribution of stresses was confirmed experimentally and theoretically only 15-20 years after Griffith's investigations. Nevertheless, Griffith found, in principle, the correct answer although he assumed that the concentrated elastic field surrounded the entire crack. Once the famous physicist R. Wood wrote that in his younger days, when he began his lecture in physics, he was two hours ahead of his students; and at the end of the lecture their knowledge was equal to his. But these historical 'two hours' that separated Griffith from his contemporaries have immortalized his name and idea.

The problem was solved by Griffith in the following way. The crack concentrated the elastic energy. Let us suppose that the crack

grew larger. Then part of the energy would be released, and this process profits Nature, as does any reduction in energy. What is this energy spent on? On fracture, of course, decided Griffith. To be more exact, this energy is spent on the formation of the two faces of the crack, i.e., on surface energy. As a matter of fact, not only metal but even a soap bubble possesses surface energy, only in metal the surface energy is, per unit of surface, 10-15 times that of a soap bubble. It is well-known that the surface of liquids and liquid films tends to contract. In contrast to liquids, this does not occur in solid metals — they are too strong; nevertheless, there is always such a tendency, and under certain conditions, when the metal is in the liquid state for instance, a metal film is very much like a liquid one. Therefore, work must be performed in order to obtain a free surface. Thus when a crack is formed, two free surfaces appear each of which carries stored surface energy. Griffith assumed that all the elastic energy that was released is spent on producing the surface energy of the two halves of the fractured metal. Griffith reasoned as follows: suppose the formation of a crack demanded more energy than the released stored energy. In this case fracture would obviously not take place. And conversely, what if the elastic energy released was more than enough to cover the energy deficiency arising from the formation of the two surfaces of the crack? Then rapid propagation of the crack would ensue and the bridge, storage tank, airplane or rocket airframe must 'die'.

All subsequent development of mechanics and physics has shown that, for the most part Griffith drew a correct picture of the process, but as concerns details he was either inaccurate or wrong. For example, he thought that a crack propagated in metal at the speed of sound. Experiments did not confirm this — the speed is at least two times less.

What is of greater importance is that Griffith's crack was absolutely brittle. That means no plastic deformation took place. However engineering practice shows that fracture is almost always accompanied by deformation which consumes a thousand and sometimes ten thousand times more energy than that needed to compensate for surface tension. It is obvious that under these conditions, surface tension becomes insignificant. The followers of Griffith, primarily the American scientist G. R. Irwin, decided that even such great plastic deformation did not interfere with the calculation of a body with a crack. It should only be assumed that the deformation is located near the very tip of a long crack. Such cracks came to be called quasi-elastic, i.e., supposedly brittle. The good thing about such cracks is that, on the one hand, the entire body of mathematics pertaining to the theory of cracks can be applied to them since the plastic zone is so tiny in comparison with the length of the crack, while, on the other hand, as tiny as it may be, it reduces the energy of the elastic field of deformation.

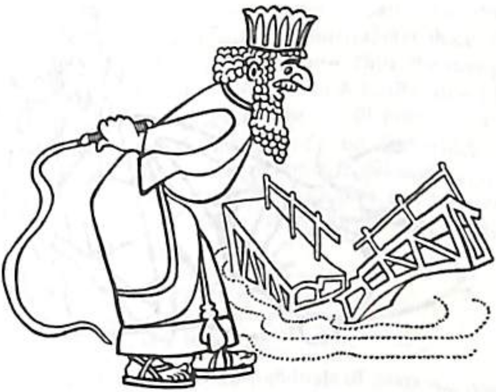
This proceeds in the following manner. First of all the nature of the stressed state in the structure is analyzed to determine what kind of crack it can lead to. There are three kinds of cracks: perpendicular, transverse (cross) and longitudinal. The first kind occurs when a sheet of paper is torn. To understand the second kind, imagine that two metal sheets are riveted together. In order to separate them you strike the top sheet with a hammer, cutting off the rivet. The defect in the rivet is a cross crack. A longitudinal crack is formed when, for example, you cut a sheet of paper with a pair of scissors instead of tearing it. For each kind of crack the stress fields around their tips (the 'ears' of the crack) were calculated long ago. As they approach the tip, the stresses grow rapidly and after they attain a maximum value, the material begins to flow, i.e., plastic deformation takes place. This is called the yield point. The extent of the area where this occurs is easily computed; from this moment the real length of the crack is its actual length plus that of the zone of plastic deformation. Now that the length of the crack, the stress at its tip, and the energy spent on deformation

are known, the force required for further propagation of the crack can be determined. And, of course, it can easily be compared with the experimentally measured force. And it is still more important to introduce that surprising characteristic of a material, its toughness or resistance to further propagation of the crack. This is proportional to the breaking stresses at the tip of the crack and is the limiting strength of the cracked metal. It is easily calculated for any kind of crack in any steel structure. Comparing it with the stresses acting on parts in one or another process of loading, it is possible to predict beforehand whether or not a structure having a crack will withstand a given load. This can all be done without testing a whole space rocket stage, but only a sample of the material it is made of.

Today this is one of the principal methods of testing strength because in real life any part of a metal structure contains numerous defects: cracks, cuts, holes, whereas it is physically impossible to test as a whole, for instance, a truss 50-100 meters long. Fortunately there is no longer any need to do this. Hundreds of laboratories all over the world, in all branches of machine building, use this method today, although twenty years ago it seemed that it was not needed.

Scientists proved to be right and gave civilization an excellent method for predicting and estimating real strength, which we will conditionally refer to as 'initial diagnosis'. What do we have in mind? An accident has occurred. It can be very serious — an oil tanker of a hundred thousand tons displacement blew up and oil poured over a vast area of the sea. Or it can be on a modest scale, for example, at the time of the big frosts the water in the radiators froze and some of them burst, scattering fragments all around (that happens too). An expert-mechanic, just like a doctor examining a patient for the first time, before receiving any test results, will say something as follows. Perhaps in a particular case, the body of the tanker was carelessly welded as a result of which the seams were not continuous. The places where the seams were poorly fused became stress concentrators. Moreover, the body of the tanker was not sufficiently rigid, and during a relatively slight swelling of the sea it constantly sagged. In time the number of bending cycles reached the critical value and due to the stress concentrators cracks began to appear in the weld seams.

There might be another variant. At the time of welding, considerable residual stresses were stored in the body of the tanker and



they were 'discharged' at the places of poor fusion, etc. Thus the initial diagnosis is of a macroscopic nature and proceeds from such concepts as stresses in the structure, energy stored in it, stress concentration, etc.

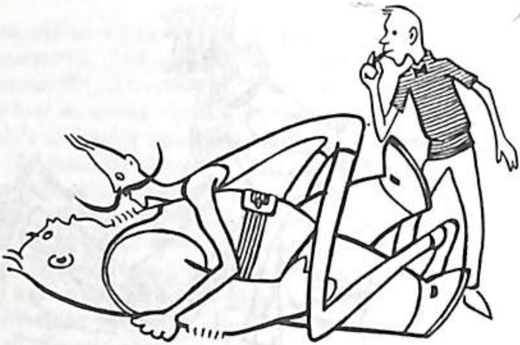
We know from an ancient Greek legend that once upon a time the Persian czar Xerxes, infuriated by the storm that destroyed the bridge across the Hellespont, ordered the sea to be whipped with a lash and put into chains. The modern engineer-mechanic being a skilled investigator, will not order the sea to be punished, but will begin to look for the primary cause of fracture. How did it begin? What happened to the atoms? These, in the first place, are the questions he will put to himself. And other investigators, physicists, will help the mechanic answer them.

THE DREAM AND THE REALITY

The cursed thread! It can be bent
Neither this way nor that.

(After Jean de La Fontaine)

Man's thoughts have always been ahead of what he could accomplish. In technology the arbitrator between fantasy and reality has nearly always been materials and their strength. They determin-



ed what man could do at any given moment. And man's desire to stand firmly on his feet has always been very great.

The 'scissors' between what is desired and what is possible, the difference between what mankind wanted to do and what it could do became apparent after the remarkable work of the Soviet physicist J. Frenkel was published in 1926. To understand its essence, let us picture the process of plastic deformation as the sliding of one layer of atoms over another, like sheets in a pile of paper or cards in a pack of playing cards are displaced. Since this process proceeds simultaneously throughout the entire plane of the sheet we are obliged to break all the interatomic bonds on both sides of the slip plane at one and the same time. The force of attraction between sheets of paper is negligible; but between layers of atoms, it is very great. Therefore, although it is possible to displace two layers of atoms with respect to each other, it requires a great shear force to do so. Frenkel found this force and recalculated it in terms of stresses that we are accustomed to. And the strength in this case turned out to be very great, 1 000 times the value of the stresses we usually encounter in everyday life. This strength was named the theoretical strength of solid bodies and it was defined as the 'ceiling' toward which we could, and should, strive.

Someone once said that a new idea is a wedge driven in thick edge first. But as concerns theoretical strength, it was quite different. Frenkel's idea was so clear and the mathematics involved so simple, if not to say elementary, that everything was accepted at once. It was adopted by the scientific community of the world which

made no mistake in doing so. It was found, in particular, that the actual strength of very fine crystals one micrometer thick, called whiskers, is very close to their theoretical one. Thus, the strength of fused silica fibers was found to be equal to 4.2 GPa; that of iron whiskers, 13 GPa; that of graphite fibers, still greater, 24 GPa. Compare these figures with the strength of good steel, which is only 1-2 GPa. By the way, the strength of cobwebs exceeds that of steel fibers of the same thickness; besides, cobwebs can be extended under tension by 20%. The words of the Soviet poet Mikhailov, therefore, are not surprising.

Even a very thin thread
Cannot be cut with the thin edge
Of a steel wedge. . .

What is astonishing is that for hundreds of years mankind did not observe this, although the amazing strength of various fibers was very well known.

But how was this knowledge made use of? It wasn't, if you discount the fact that in the XVIII century cobwebs were indispensable . . . for preparing canvases for painters in the Tyrol Alps. They were stretched on cardboard and then pictures in water colors were applied to the canvas which was so strong that it withstood the impression of metal plates. It is also known that a German museum displayed a glove made of cobwebs. According to J. Bersier, a mad German physicist destroyed it in an attempt to reproduce cobwebs chemically in order to weave bullet-proof vests for soldiers. A French naturalist gave an account of the extraordinary strength of the web of a Madagascar spider. Cloth made from it surpassed all expectations. Nothing more needs to be said. But now mankind is rapidly making up for lost time.

The metal fiber 'cobweb whisker' is an indispensable material for the sighting cross-lines of optical instruments. Very delicate microscopic springs are made from these 'whiskers'. Extremely strong ropes are made of the finest wires. And, finally, fibers are the basis for manufacturing composite materials which are widely used throughout the world in combat and civil aviation, in cosmonautics, in the textile industry, in hospital and commercial equipment, in automobiles, boats, musical instruments and for many other things. This is how an American journal evaluates the significance of a new composite material made on the basis of graphite whiskers finer than human hair: in aviation the substitu-

tion of parts made of the composite material for those formerly made of aluminium will reduce the weight of the plane by 15% and will make it possible for a combat jet airplane to increase its flight range by 10% or its fighting equipment by 30% at the same refuelling. For civil airplanes this means an increase in flight range and payload, and presumably the fares might be reduced.

This, for instance, is how rocket airframes of large diameters are made. A wooden frame having the form of a rocket is bound by a layer of thin fibers (whiskers). This is then coated with a layer of epoxy resin; then another layer of fibers is added; then epoxy resin, etc. As a result, a multilayer wall is created that is light and strong. That is how columns and towers many meters high will be made for the chemical industry, as well as cylinders of powerful presses and containers for compressed gases. The time is near when superstrong materials on the basis of the finest fibers will virtually conquer modern machine building and lead to the appearance of light passenger cars that weigh only 100 kilograms, giant bridges as light as a 'feather', and airplanes as light as 'snowflakes'. And all these will be strong and absolutely reliable. The following words of the Soviet poet Leonid Martynov come to mind:

The wonderful thread as bright as a ray,
That passes through the eye of a needle,
Will neither decompose nor wear away. . .

But why, when talking about theoretical strength, do we repeatedly speak of whiskers? What about monolithic metals which form the basis of machine building? The fact is that, unfortunately, theoretical strength has not been attained for monolithic metals, although that does not mean that scientists have not been working on it. Steel has been obtained that has a strength of 3, and even 6, GPa; but this is still very far from the theoretical strength.

Why has this been attained for fine crystals, while the strength of monolithic metal bars, ingots, rolled products, has not reached the theoretical value yet?

THE PRICELESS FAULT

A crocodile in wrinkled metal loafing. . .

Louis Simpson, *Walt Whitman at Bear Mountains*

So, why?

This is one of the most important questions among those evoked by the work of J. Frenkel. But not the only one. For exam-

ple, why is the actual strength of crystals hundreds and thousands of times less than the theoretical one? Why are pure metals softer than alloys? Why are polycrystals harder than monocrystals? The twenties did not bring answers of any consequence to these questions.

1934 was a year of great changes. The English physicist H. Taylor from Cambridge University and the Hungarian scientist E. Orowan suggested the hypothesis that in a crystal there is a specific defect, a dislocation that seriously alters the properties of a crystalline material. They proceeded from the assumption that if the crystal were ideal, it would be necessary to apply a stress equal to the theoretical one in order to deform it. And since in reality the stress of deformation is insignificant there must be some concentrator that concentrates the applied load in a small portion of the crystal. They regarded a crystal as a thick book where the layers of atoms are sheets of paper. Then an additional sheet of paper the size of half a page is inserted like, in the words of the poet O. Mandelshtam, "the beak of a crane thrust into alien borders". It is obvious that this extra layer of atoms, or extra plane, is broken off in space. Let us further imagine a slip plane perpendicular to the sheet of paper and passing along the edge of the extra plane. On both sides of the slip plane the atoms have interacted, 'grasped' each other. But the atom at the edge of the extra plane is a solitary one: there is no atom face to face with it. Nevertheless, the 'desire' to come in contact with another atom is present. It is this atom at the edge of the extra plane that is capable of working wonders.

Should we apply a shear force to the crystal, the atoms in front and behind the dislocation, with the exception of two or three on both sides, cling tightly to one another. Our 'lone wolf' is another matter. Originally it was exactly in the middle of two atoms of the lower row and a little above them. But the external force shifted it slightly to the left. Taking advantage of this, it 'grasped' the left atom of the lower row, tearing it away from its former neighbor above it. Consequently, it was no longer the edge of an extra plane and thus became part of a group of associated ordinary atoms — it is good to be inconspicuous, like all the others! And the extra plane was no longer an extra plane; another extra plane appeared, originating from the 'unfortunate' atom that had been deserted by its 'brother'. This plane was situated to the left of the former one, by one interatomic distance. The atoms again came in close contact with each other, drew up their ranks, and the dislocation shifted to the left by one interatomic distance. Still another displacement, a

breaking away and a new act of uniting and so on and so forth . . . The dislocation runs to the left along the crystal, each time substituting the atoms in its extra plane, retaining this plane and its own shape.

The reader has a right to ask a direct question: where did the dislocation come from? Of course, we do not insert a layer of new atoms each time like a page in a book.

This is a most complicated question, one that has not been fully explained by the many-volume theory of dislocations. There are several processes in which dislocations originate in crystals; for instance, in crystallization from a fusion. Dislocations appear on compression of some microscopic pores in a material. Dislocations can play the role of 'parents' who breed other dislocations. But it must be emphasized that this is a very complicated question.

Let us consider a situation that does not occur in real life but can serve as a very convenient example for explaining dislocations. Let us apply a shear force to the surface of a crystal and compress its upper part so that above the slip plane three atoms cover two lower atoms. To achieve this we had to deform the crystal by one interatomic distance and as a result we virtually obtained a real dislocation. If we now apply pressure, the dislocation will propagate as we have already described. Roughly speaking, a solitary atom at the edge of the extra plane can now 'grasp hands' with the atom that faces it, and moving closer up, turn over the function of an extra plane to another row of atoms. If on the side surface of an undeformed crystal we drew a network of parallels and meridians that passed exactly along the atomic rows, then with the appearance of a dislocation, this map would lose its geometric proportions and regularity.

To the right of the dislocation, the upper and the lower part of the crystal are displaced by one interatomic distance. To the left, there is no displacement. As the dislocation moves to the left it is followed by the deformed region. And when the dislocation runs along the whole crystal and comes out on its surface, it appears that the upper half of the crystal will have shifted with respect to the lower half by one interatomic distance and the dislocation disappeared.

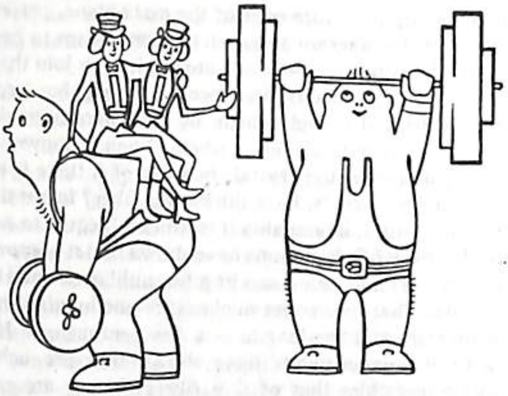
So what is a dislocation? It is a linear defect of a crystal lattice. Why linear? That is a question that is easily answered — it is the edge of an extra plane. In the diagram we have mentally drawn, it is a point, one atom. Actually, there are many 'lone wolves' — they

are situated along the entire edge of the extra plane, perpendicular to the plane of the diagram and each of them craves to become indistinguishable from the rest of the atoms, i.e., to join their ranks. But to do so it must occupy the place of its neighbor beneath the slip plane, shifting the displacement by one interatomic distance.

So, a dislocation is a line, a fiber. When it moves it causes plastic deformation of the crystal. In front of it there is no deformation; behind it, there is. How thick is the fiber? In our diagram it is equal to one atom; in actuality it is 'thicker', equal to 5-6 atoms. And how long is it? Calculations have shown that it is approximately the size of a crystal, i.e., it can be a few millimeters and even centimeters long. That means the thickness is one hundred-millionths of a centimeter, and the length — a few centimeters. Just like a fiber, isn't it? Experiments have shown that the behavior of dislocations resembles that of thin fibers — they are capable of deflecting, adhering to defects and sometimes even of forming fabric by interlacing lines. As you know fabrics possess rather considerable strength. That is why when many dislocations are interlaced they hinder each other from moving and make the crystalline material quite resistant to plastic deformation, that is, stronger. There are not very many dislocations in monocrystals — about a million per square centimeter. This is not a small figure, but because the dislocations are not distributed uniformly, considerable areas of the crystal are free from them. And if in such an area a dislocation appears, its propagation is not impeded. That is why monocrystals are not very strong.

Polycrystalline materials are another matter. For example, the density of dislocations in steel is thousands and millions of times that of monocrystals. In this case the dislocations cannot move independently of each other. They interact. The dislocation fibers form a complex three-dimensional structure that resembles an entangled ball of fiber. It is obvious that such metal is deformed with greater difficulty. It is stronger.

Other things take place in alloys. What happens is that the foreign matter — the alloying atoms — tend to surround the edge of the extra plane. Roughly speaking, they are drawn to the 'lone wolf' which is constantly in search of 'brothers'. Furthermore, it appears that a dislocation is capable of generating an elastic stress field around itself. It 'sucks' up the foreign atoms. As a result of this the dislocation line which was slim and elegant in pure metals



grows stout and spreads out in alloys, losing its mobility and sometimes simply becoming incapable of moving in space. The alloying foreign atoms surrounding it play the role of nails that fasten it to the crystal lattice. Well, if the dislocation is immobile, there can be no plastic deformation. Consequently, alloyed metals are stronger than unalloyed ones.

It is now clear that an abundance of dislocations leads to the suppression of plasticity, and consequently, to higher strength in metal. But does this mean that many dislocations are always needed for great strength? This question is too direct to be a correct one.

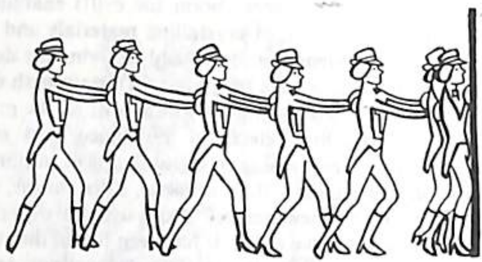
Indeed, what about whiskers? Their strength is close to the theoretical one. How many dislocations are there in them? Perhaps there are many? As a matter of fact there are hardly any. Some whiskers have only one dislocation, if any. And it is such dislocation-free crystals that have the maximum strength.

If you think about it there is no contradiction here. The main thing is that to obtain great strength it is necessary to suppress plastic deformation. And this can be attained in two ways: either by eliminating the principal cause of plastic deformation, i.e., dislocations, or by packing the metal with so many of them that they cannot move because of lack of space. Dislocation-free crystals (whiskers) result from the first case; special heat-treated steel, having a great number of dislocations per unit volume, results from the second one.

Thus, dislocations are a great boon (or evil!) enabling us to understand what takes place in crystalline materials and to consciously influence this phenomenon. By only altering the density of dislocations we can, over a wide range, attain the strength we need. And not only strength. Dislocations affect almost all the properties of metals: their ductility, electrical resistance and magnetic characteristics. Almost everything in metal that is of importance to man depends on dislocations: their number, distribution, nature.

What do I mean by their nature? Did I use this expression by mistake? No, I did not make a slip. It has been found that there are at least two varieties of dislocations. The dislocations we had in mind up to now are usually called edge dislocations, based on the existence of an extra plane (its edge). There is another kind, just as important, called screw dislocations. Such dislocations have no extra plane; they resemble a pair of scissors cutting a thin sheet of tin. One side of the sheet turns down, and the opposite side turns up, as though the scissors twist the two halves of the sheet with respect to one another. But whereas scissors actually cut the metal, a screw dislocation only displaces it. In some ways it resembles scissors with blunt blades which cannot cut the metal but only crumple and deform it. After a screw dislocation passes along the metal, its parts are twisted away from each other. As in the case of an edge dislocation, there is no deformation in front of the dislocation; deformation is behind it.

Thus, there are two varieties of dislocations — edge and screw, something like two surnames, two clans. But dislocations must have given names as well as surnames. As a matter of fact there are a great number of different edge dislocations which must be distinguished from each other. The main characteristics of a dislocation are its size and the direction of the displacement it causes. Displacement in a crystal can take place in different planes, after which both parts of the crystal can be mutually displaced to different extents. These two factors are taken into account in solid-state physics by introducing the Burgers vector. Its dimension and direction are the 'name and patronymic' of the dislocation. For example, we say: a screw dislocation with the Burgers vector of a length of one interatomic distance, directed along the side of a cube. But in practice it is simply designated by the letter $\bar{b}$ and is equal, for instance, to a [111]. This designates that the Burgers vector is directed along the diagonal of a cube and its length is equal to $a\sqrt{3}$, i.e., that of the diagonal.



Let us sum up. Plastic deformation of crystals is brought about by defects, dislocations whose specific feature is the concentration of stress applied to the slip plane on one small spot, as a result of which the dislocations move easily and rapidly. The propagation of a dislocation somewhat resembles the motion of a caterpillar, every step of which consists in the displacement of ridges or wrinkles (recall the epigraph at the beginning of this section).

Sometimes a dislocation is pictured otherwise. It is very difficult to move a carpet spread out on the floor. But form a wrinkle in it and it will become easy to move the carpet with your foot. As a result, the carpet will be displaced by the length of the wrinkle. The same can be done with wet oilcloth.

What is a dislocation — an abstract hypothesis, a scientific concept or an everyday reality? Of course, it is a reality. In fact, in Taylor's time it was merely a theoretical scheme, a good idea, a model. But today there are tens of methods that make it possible to see dislocations as clearly as a person passing in the street, by means of an electronic microscope; to observe it using X-ray diffraction analysis and an ordinary optical microscope. Long before our victory over these defects, Iosif Utkin, in his poem *Two Worlds*, wrote:

. . .Not once
And not twice
The crosshairs
Of the sight
Showed dislocation of the mark. . .

But why are dislocations of such interest to us? Why do we devote so much attention to them? What have dislocations to do with fracture? Have they any relation to cracks? These are pro-

bably the questions a moderately skeptical reader would like to ask me. The answer is quite simple. The fact is that dislocations 'hold in their hands' the key to the world of strength of crystalline materials. It is precisely dislocations that decide the final diagnosis.

FINAL DIAGNOSIS

> **. . . A sudden jolt tore asunder**
> **the networks of molecules under stress. . .**
> (After V. Nazarov)

The reader remembers that mechanics could not determine what started fracture and what happened to the atoms.

The time has come to consider this problem from the position of physicists.

It would be wrong to believe that everything connected with this problem is obvious and already established. There is still much uncertainty and vagueness. Let us take, for example, the principal question over which many 'lances' and opinions have been broken for many years: is plastic deformation always necessary for the appearance of the first microcrack or, as physicists say, the incipient microcrack?

The outstanding Soviet scientist A. V. Stepanov was the first to advance the opinion that microcracks cannot originate without plastic deformation. For tens of years this point of view was generally accepted. It predominates at the present time too, but now it is not the only possible one. The opposite view is also quite acceptable. Otherwise it would be impossible to explain facts that are observed in experiments. It is also important because the imagination and fantasies of man should not be hampered in any way, even when contradictory viewpoints that seem to exclude one another are sometimes placed side by side.

At the present time two types of cracks are differentiated. First of all, the ideally brittle crack, what is called a force crack, because it originates due to the mechanical cleavage of a crystal. What occurs is something like the flaking of mica or the tearing away of old wallpaper or photographs pasted in an album. In this case interatomic bonds are broken under the direct action of external

forces, and one atomic layer is torn away from the adjacent one. The characteristic feature of such cracks is the gradual curvature of the surfaces and their convergence at the tip of the crack, one interatomic spacing apart. Can this explanation be considered complete? Of course not; it is merely an image, an idea, a model. The question would be understandable only after we ascertained what had taken place between two atoms. How were the interatomic bonds ruptured? What happened to the electrons in the space between the layers being separated? There are many questions but, unfortunately, there are no answers to them yet. We do not know anything about the mechanism of rupture of the crystal lattice. Meanwhile, experiments show that brittle cracks do exist and they can be seen in considerable parts of crystals in which no dislocations are present.

As concerns microcracks of the second type, dislocation microcracks, the situation is much better. We understand how they are formed. Of course our knowledge is far from thorough. Still, we do understand. Let us begin with the nature of dislocations. A dislocation is not a solitary defect; it appears in groups. It is not indifferent to its neighbors and is capable of coexisting with them on friendly or unfriendly terms, just like people with different and difficult natures. Things can come to such a pass that one dislocation may swallow another one. Nevertheless, it is obvious that it is absurd to speak of 'good' and 'bad' dislocations, just as there is no sense in speaking of a 'clever' lamp or a 'stupid' bookcase.

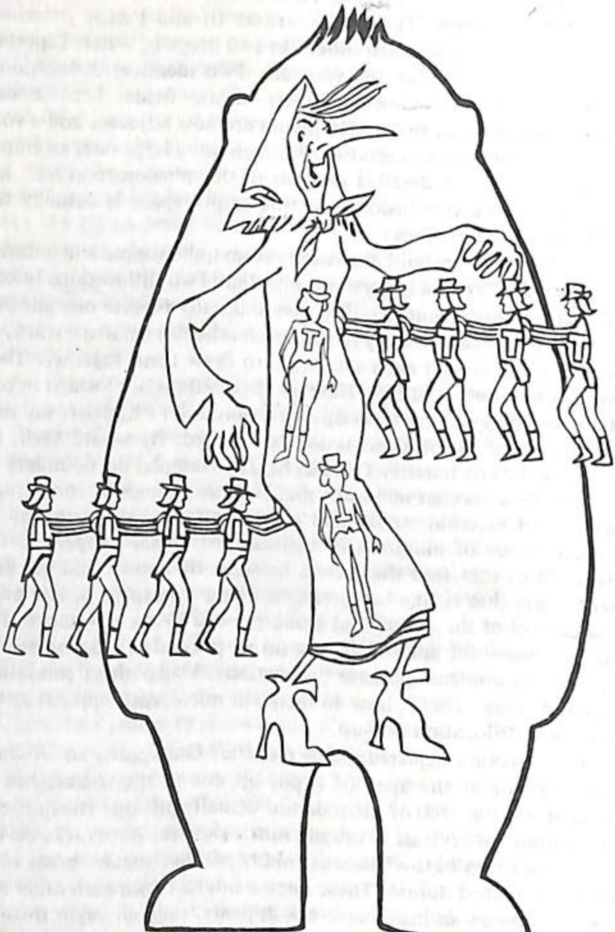
Let us carefully examine what happens. First of all, let us assume that two edge dislocations are in one and the same slip plane and their extra planes lie on one side of it. In this case, there are two possibilities at the disposal of the dislocations. The first one is to live like good neighbors; as the saying goes, 'the more the merrier'. The reader remembers that the formation of dislocations is connected with the insertion of an extra layer in the material. That means the space surrounding the dislocation is deformed. As the dislocations, due to the action of external forces, are drawn together, their elastic fields begin to interact and hinder further convergence. If, however, the number of dislocations in a slip plane is great, the stresses surrounding the piling up of dislocations can be quite considerable. That is understandable — the dislocations are pressed closely together and the moment may come when they will behave like scorpions in a jar. They will begin to devour each other.

This word is not very precise. First of all, it is not clear who is devoured by whom. The Soviet writers Ilf and Petrov described twins "who resembled each other like two drops of water. Especially the first one." Judge for yourself. Two identical dislocations, overcoming the resistance of their elastic fields, become one dislocation. Both of their extra planes are now adjacent and a void appears under their last atoms. Although not a large one, an empty space is present. A detailed analysis of this phenomenon has led scientists to the conclusion that this empty space is actually the nucleus of a microcrack.

If what has been said above may seem quite simple and natural, in reality the process is very complicated. Two dislocations in one slip plane cannot simply unite; they mutually repulse one another like two sports cars that try to pass each other on a narrow track, as long as there are no external forces to draw them together. They can coalesce only if about 200-500 dislocations are located in one plane and they can move in one direction only. Physicists say that the pile-up of dislocations is locked, barred. By what? Well, by anything, by any barrier. This can be, for example, the boundary of a grain, or a foreign inclusion that is large enough or some other defect. An external stress field exerts pressure on the tail of an orderly queue of hundreds of dislocations. What happens to the dislocations that find themselves between the crowd and the barrier? Why, that is like being caught under a heap of people piled one on top of the other, and being pressed to the pavement. The dislocations at the apex of the pile-up are pressed against the barrier by the entire queue of these dislocations. Under these conditions they can unite. That is how an incipient microcrack appears at the apex of a dislocation pile-up.

Is the picture depicted above realistic? Only partly so. A crack can originate at the apex of a pile-up due to the coalescence of dislocations but 500 of them do not actually pile up. The queue of dislocations in crystals is usually much shorter. But cracks do appear, don't they? How? Because many parallel queues 'break into' adjacent 'locked doors'. These queues interact with each other and just as soon as an incipient crack appears, they all begin to fill it with dislocations. And, as the reader remembers, each dislocation brings the crack its empty space under the extra plane, causing the crack to grow.

Another means of evading the piling up of a great number of dislocations is to overcome the mutual repulsion ('hostility') of



dislocations when their number is limited. In this case, gradual loading is substituted by dynamic loading. It is necessary to accelerate the dislocations and draw them together at a great velocity. Then, the dislocations possessing a large store of kinetic energy will exchange it for potential energy and break through the elastic barriers enclosing other dislocations. As a result, at a much smaller number of piled-up dislocations, coalescence and the formation of microcracks can be expected. Calculations have shown that the velocity of dislocations in this case must be almost equal to that of sound (in steel, for instance, 3-5 km/s).

Up to now we assumed that the reacting dislocations were of the same sign, i.e., that their extra planes were located on the same side of the slip plane. However, unlike dislocations can also come into conflict. In this case the chances of coalescence are greater. The point is that the elastic fields of unlike dislocations are attracted to each other. Therefore, the coalescence of dislocations occurs readily and naturally and vacancies are formed where one extra plane comes against another one. Physicists simply call them holes. If many unlike dislocations move towards each other in a slip plane, it becomes an area full of holes. It is believed that in some kinds of mechanical loading, for example during creep, a gradual deformation of metals at elevated temperatures, these vacancies can group together and form microcracks. Under conditions of ordinary, rather rapid loading there is not enough time for diffusion of these defects and that is why they most likely do not play any part in fracture. But in parallel and adjacent planes two pile-ups of unlike dislocations, moving towards each other, get stuck. Each plays a dual role. In the first place, it is a barrier for the opposite pile. In the second place, it is a wedge compressing its two head dislocations. As a result, conditions for the coalescence of dislocations are more favorable and it takes place at a relatively small pile-up. And the crack grows more rapidly because it now has two nursing mothers.

The reader should note the close connection between dislocations and incipient microcracks. In the stage when the latter is only two united dislocations, the crack is practically inseparable from them. Plastic deformation and fracture merge into a single continuous process as a natural phenomenon.

In addition, thermal motion causing the crystal lattice to vibrate, makes the atoms constantly oscillate at the lattice points. The dislocation line also vibrates — on it microscopic waves appear

and disappear. At any given moment such a wave consists of a kinking of the dislocation line in the slip plane. This indicates that in a small area there appears, besides the main extra plane, another one parallel to the first one, as if the dislocation has moved ahead. This process, as physicists say, is of a statistical, arbitrary nature. It would be presumptuous and wrong to claim that a kink will appear in a particular dislocation at a particular spot. However, such a process can always be expected to occur in a sufficiently reliable number of dislocations in a given area. To draw an analogy, we cannot foresee whether we will encounter a man 1 m 80 cm tall at the next street corner in the following minute, yet there are statistics available that tell us how men are distributed according to their height in each country. For example, recently in the Soviet Union out of 10 000 men from 25 to 35 years old, one or two were 190 cm tall, three or four, 187 cm tall, eight to ten, 185 cm, and three hundred, 182 cm. The average height of most of the men was 168 cm. Therefore, if we put the question as follows: what are our chances of meeting a man 180 cm tall at the next corner of a rather crowded street, we can try to guess the answer.

The same applies to kinks on dislocations.

Yet the Leningrad physicists A. N. Orlov and V. I. Vladimirov have shown that such reasoning, that at a first glance seems to be unreliable, leads to quite reliable results. It was found that when kinks of thermal origin appear on two dislocations brought together under pressure, they tend to coalesce more readily and an incipient microcrack originates more easily. And if previously,

theoretically, a fantastic number of dislocations were needed (200-500) in a dislocation pile-up to form a crack, thermal excitement of a crystal lattice and dislocation lines reduces this figure five times; and a pile-up of 40-100 dislocations is quite realistic.

A column of dislocations or a dislocation pile-up is one of the chief 'fighting' formations of dislocations. In such ranks their strength is augmented because their own elastic fields are added to the external pressure. Such a system possesses a great 'break-through' power. Imagine the following situation: the pile-up presses against a barrier which is so firm that it is impossible to break through it. The external stress grows and tens of dislocations increase it. At the apex of this dislocation 'chisel' the situation becomes critical. . . Now the stress reaches its ultimate strength. We know that in this case the material is bound to break. As a matter of fact, a crack suddenly appears at an angle of 70° to the pile-up. This process proceeds more readily if several pile-ups simultaneously attack the barrier. It was found that screw dislocations, just like edge dislocations, are also instrumental in attaining stresses equal to the theoretical strength. Only in this case the crack appears directly in the slip plane of the dislocations, i.e., in the plane of the dislocation pile-up itself.

Would the picture depicted above satisfy physicists? It would not for the following reason. Stresses are certainly concentrated at the apex of the dislocation pile-up and the material in the vicinity of the barrier is without doubt prepared to fracture. But it is not at all clear how the rupture of bonds of the crystal lattice of a size of at least two interatomic distances initially occurs. The above mechanism was described 25 years ago, but it has not as yet helped

to answer this question. Therefore, I would say that the nature of the incipient crack is strange and not altogether natural. The conditions for its origination are present but the necessary 'trigger' is absent.

. . . A very strange guest, a mysterious guest.
Right through the wall he did pass like a nail,
Driven in by someone. But what was his aim?

(After B. Akhmadulina)

In this respect another mechanism of crack formation is also indefinite. It was proposed by Soviet and American physicists. This mechanism consists in the following. Dislocations piled up in a slip band are blocked by some barrier. As an external force fills this band with dislocations, the slip plane is bent under the action of the numerous dislocation extra planes located above it. What happens is similar to the flaking of film on patent-leather slippers. When lacquer is applied to the leather, the resulting film adheres to it. In the process of walking the leather is constantly bent. But the leather and film on it differ in flexibility and the stress in them is also different. In case of faulty adhesion, sooner or later, the film begins to separate from the leather and crumble. It is quite easy to understand the conditions for the splitting of the material along the slip plane. But it is not clear how this happened, how it started.

One of the possible answers to this question was suggested by V. L. Indenbom and M. Kh. Blekherman from the Institute of Crystallography of the USSR Academy of Sciences. They noticed that the weakest spot in dislocation pile-ups was the dislocation itself. They found that the core of the dislocation — its nucleus — could split up under certain conditions. In general, it should be remarked that the nature of what occurs in the nucleus of an edge dislocation is complicated and inadequately investigated. The surroundings of the edges of extra planes will reveal many unexpected things in the future. One of them was observed by Indenbom and Blekherman. The core of a dislocation is a material with an interrupted continuity. There are grounds to assume that a hollow channel passes along the edge of an extra plane. The stress in the nucleus of a dislocation is very great and at the present time it still cannot be calculated directly. Accordingly, the mechanical properties of the dislocation nucleus are sure to be worse than in the matrix of an unbroken crystal. We refer to the tensile and shear strength of the

material. And as strange as it may seem, fracture can begin straight from the nucleus which serves as the initial embryo of a microcrack. The question is how the microcrack will begin to grow. It has been established that in plastic crystals the microcrack propagates along the slip plane. In brittle crystals the drawing together of dislocations leads to a rearrangement of their nuclei and to the opening up of the crack directly along the extra plane. What happens to the dislocation then? It destroys itself, like in hara-kiri![1].

Thus, science is provided with three theoretical mechanisms of crack generation and their variants. Are these the only possible cases? Of course not; there are many others. Up to now the dislocations forming cracks moved in one and the same slip plane, whereas they are capable of moving in different planes of the crystals. What can be expected when such dislocations converge? Theory says that they interact so violently that they themselves vanish, giving life to dislocations located in the cleavage plane, i.e., in the plane where rupture occurs. Since, as a rule, slip takes place along many planes, in the cleavage plane there are formed many such dislocation offsprings which combine to form a crack. This mechanism, proposed by the English physicist A. Cottrell, brings to mind two skiers gliding down a hill and colliding at the bottom. Imagine how their skis strike and cross each other, becoming entangled. In such a situation the skiers — dislocations — cannot glide any farther. What is characteristic is that, whereas the two gliding dislocations prior to combining with each other were means of plastic deformation, the newly formed dislocation is an instrument of fracture. What happens is similar to when two persons collide in the door of a trolley-bus and the coat button of one of them gets caught in the nylon net bag of the other, which usually results in the button being torn away or the coat being torn. In most cases this is a Gordian knot that can be severed only by cutting it. But . . . Cottrell proved that sometimes the 'glued' dislocations, which have seemingly lost their identity and even completely disappeared, can be separated. In the situation in the trolley-bus, that would mean patiently freeing the button from the bag, which is not always possible. In the language of dislocations this is as much as saying that the crack-forming dislocation dissociates into the two original slip dislocations. Something like in the poem *What Train will Come*? by the

[1] Hara-kiri is a ritual suicide by disembowelment, formerly practised in Japan. — (Editor's note).

American poet William Jay Smith, backwards means forwards, because the crystal escaped fracture and returned to its monolithic state, to strength.

A whole group of fracture mechanisms is associated with the existence of boundaries in crystalline materials. In metals it is grain boundaries; in monocrystals, subgrain boundaries. In both cases we have in mind rows of dislocations. In monocrystals the rows are simple enough. Roughly speaking, they are edge dislocations situated one behind another. The extra plane of each dislocation ends at the boundary and all together they cause one half of the crystal to turn away from the other half. The higher the density of dislocations at the boundary, the more extra planes 'die' on it and the more crystals are turned about. There are a great number of such boundaries in crystals and they form complex three-dimensional space patterns of arbitrary shape. When viewed from a distance the boundaries of a crystal are not discerned very well, but if the crystal is brought close to the eyes and turned in a beam of light, a faint glow is reflected from various parts of it. These are its largest subgrains. A great number of minute subgrains are hardly noticeable.

During deformation of a crystal the dislocations in it move along different crystallographic directions and they periodically cross the boundaries. What happens then?

If adjacent subgrains are not turned about too much, i.e., if the density of dislocations at the boundary is small, a slip band can pass the boundary easily and smoothly. But as the angle between adjacent crystals grows, the subgrain boundaries become stronger. Now it is necessary to apply a definite pressure for dislocations to break through. At last there comes a moment when an intergranular linkage becomes a powerful barrier that hampers the movement of all the dislocations pressing against the boundary in the slip band. What happens later is described by the Englishman A. Straw and the Frenchman J. Friedel. Under the pressure of the 'crowd' of dislocations, the stress in the area where the dislocation pile-up collides with the boundary grows rapidly and . . .

Right through the thin partitions
I'll pass like light. I'll pass
Like an image enters an image,
Like one thing penetrates another.

(After B. Pasternak)

The boundary breaks down like the wall of an old house struck by the blade of a bulldozer. Part of it remains in place and part is displaced and a crack appears at the boundary, completing it so to speak.

A group of Leningrad scientists headed by V. A. Likhachev pointed out still another possible interaction between slip bands and a dislocation boundary, with milder, evolutionary character. Imagine the following: a car, accompanied by the screeching of brakes, turns sharply and leaves a dark stripe on the asphalt road, a thin layer of rubber from the tires, that sticks to the road due to pressure and the resulting friction. A sharply turning dislocation also leaves a mark. When a slip band passes from one crystalline grain to another, the curve of the trajectory at the boundary causes the 'residue' of a dislocation caught in the intergranular linkage to settle in it.

A dislocation surmounting the boundary between two grains can be compared to a skier who wants to ski down a small hill. If his speed is high, he will jump in the air and land some distance beyond the hill, just like from a spring-board. In order to glide smoothly down the hill, his speed must be low enough: then the force of gravity has time to press the skier down to the surface of the hill. If a dislocation moving along a slip plane comes upon an intergranular linkage, while on the latter, it must turn through an angle equal to the disorientation of adjacent grains and move along a new slip plane. But this means it must change its Burgers vector which is only possible when another dislocation appears that, according to the rules for the summation of vectors, will have a Burgers vector that will form a triangle with the vectors of the initial dislocation and the dislocation passing into the second grain. Roughly speaking, the role of this dislocation is to make the slip dislocation 'lick' the boundary and to pass from the slip plane of one grain to that of the other. If a large number of slip bands attacks the boundary, a great number of dislocation 'residues' originate. When they merge together, cracks appear at the boundary. These dislocations can form their own wall. Then, theoretically, an incipient crack can appear at the edge of the wall like in the Straw-Friedel mechanism.

The Soviet physicist V. L. Indenbom, and later, a number of American physicists found another variant of crack formation. Due to the action of a slip band pushing against an intergranular boundary, a step is formed in the latter. This is similar to the way

the blade of a bulldozer presses on a thick wall of raw clay. Calculations show that in the vicinity of such a step enormous internal stress would arise (no wonder, since the process proceeds in a monolithic material); the stress would be so great that sooner or later a microcrack would appear instead of the step. As it takes the place of the step and plays a conciliatory role (when it appears the stress will naturally diminish), it is called an accommodating crack. In other words it is an opportunistic crack adjusting the two halves of the crystal and the two parts of the displaced boundary to co-existence.

It is hardly possible in a short narrative to say everything that is known about the generation of cracks. But it would be unpardonable to say nothing about twinning and its controversial role. It is a very unusual and exotic defect. A dislocation is microscopic in size and invisible to the naked eye. A twin is another matter — it can be the size of half a large crystal. In monocrystalline materials, for example, bismuth, calcite, zinc, and even in steel, twinning assumes the form of bands that can be clearly seen. As a rule, conventional steel always contains a great number of twin bands. This is due to the origin of twins — they are readily formed under dynamic loading. And since in its production steel is repeatedly subjected to various kinds of impact and deformation at high speeds of loading, there is an incredible number of twins in it. There can be several tens of them in each grain. And as a grain is hundredths of a millimeter in size, a cross section of a piece of metal equal to 50 cm can contain about a million twin bands, each of which affects its strength. This is of great importance because there is no other defect in metal that has been explained so vaguely. And no defect manages to be so useful and so harmful at the same time.

Well, the time has come to say just what kind of a defect this is. Actually it is the area of a reoriented crystal lattice, at a specific angle. Let us take a crystal and clamp part of it in a vice, pressing on the other part. Under a definite load the crystal will rotate and occupy a position that is the mirror image of the initial one.

It is of interest that the body of the twinned crystal has the same crystal lattice as that of the 'mother' part and is not in any way distorted. In other words, twinning only turns the crystal around but does not saturate it with defects. The boundary between the main and twinned parts of the crystal is a different matter: it is just

stuffed with dislocations which are called twinning dislocations. As a matter of fact, twinning is a variety of plastic deformation — the changing of the shape of a crystalline material.

In a real crystal, twinning usually proceeds in relatively narrow bands, called twin bands. Such a twin has two boundaries with the main crystal. On each of them there are dislocation walls producing a field of elastic stress around each twin band. An even stronger field originates in polycrystals because in the process of twinning within the crystal the material is displaced, the external boundaries of the body remaining the same. Thus, twinning is capable of increasing the stress level of the metal in its microvolumes. This is one of the circumstances (although not the most important one) that, in case two parallel twin bands are situated close to each other, results in the formation of vacancies of a definite crystalline configuration between them, called type I Rose channels. These are virtually incipient microcracks.

Of even greater interest is the crossing of twin bands. In the site where this occurs the crystal splits up into a great many minute crystals, a micron and a fracture of a micron in size. This is a type II Rose channel — a crack filled with broken material. Since the volume of broken material is always greater than that of compact crystalline material, this incipient crack presses on the surrounding crystal and causes additional microcracks to appear.

The reversible nature of twin bands was detected by R. I. Garber. Twins are considered to be elastic formations. Hence when the stress is removed or an opposite stress applied, they can vanish. V. A. Fedorov and the author, on the basis of this conception, have shown that type I and type II Rose channels are also reversible. After elastic twins disappear they can 'heal' and nothing will threaten the strength of the crystal.

However, this is unusual for twins. More often they form cracks that are irreversible, and they have plenty of opportunities of doing so. For example, twins can generate dislocations and allow the latter to pass ahead of them. Such dislocations from two twins can interact and form microcracks.

Twins do not miss the chance to form cracks in other ways. Thus when they cross the surface of a metal with an intergranular boundary, with a non-metal inclusion, or in general, with any sufficiently rigid macroscopic barrier, the appearance of a crack can be expected, although the mechanism of their generation is often not

clear. However, it is unquestionable that twinning is dangerous and a potential source of incipient microcracks in metals.

Does that mean that twinning is an evil, that it is absolutely harmful?

It is here that the inherent nature of twins — incredible 'versatility' — emerges.

The fact is that twinning is far from always an evil. Let us begin with the fact that when a load is applied to metal, twinning plays the part of a damper. It quickly comes into play and, passing along the cross section of the metal relaxes it, i.e., extinguishes the external load by causing rapid plastic deformation. This process is especially effective during dynamic loading, i.e., very rapid loading. While dislocations only begin to free themselves from their atmosphere, to tear themselves away from their long-occupied places in the crystal lattice, the twin has already begun to move rapidly ahead. A. P. Korolev and the author have ascertained that it moves at a speed of 2-2.5 km/s. And all the time while it is racing along the crystal at a break-neck speed, it removes the external stress, thus acting in favor of the strength of the metal. In the process of dynamic loading of steel, for 20 μs twins remain face to face with the external load, relieving the tension until the main defence forces of the metal, the flow of dislocations, approaches. It is they that in this way receive the first blow and defend the metal.

Well, everything is clear the reader will say, twinning is a boon. But this chameleon brings us a new surprise. While it is defending the metal, absorbing the external load, it is already 'thinking' of the future. And its thoughts, unfortunately, are 'dark'. Even in the process of their seemingly defensive race, a race for life, twins begin to create microcracks. Alas, we know what this leads to sooner or later.

A strange defect, isn't it? But since it does exist, how does the metal live with it? Perhaps we can rely on twins here after all? Maybe they will sustain strength? Is that possible?

Twins are true to their nature here too. On the one hand they are capable of hindering a macroscopic crack that propagates in the metal. On the other hand they embrittle the metal, reducing its resistance to cold shortness. That is the way it always is: on the one hand. . . on the other hand. . .

'ADOLESCENCE' OF A CRACK

. . .The moment between light and dark. . .

(After V. Bryusov)

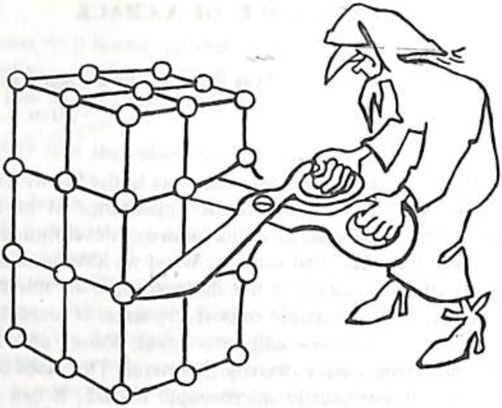
Now we know about the first moments in the life of a crack — from the application of load to the appearance of an incipient microcrack. The second stage of its vigorous development is slow and consists in its subcritical growth. What we have in mind is that at this stage of its history it is not dangerous, is completely under control. Its growth is possible only if the stress is increased. This guarantees that a fracture will not 'break loose' and begin to ruthlessly, indiscriminately destroy the metal. This does not mean that the crack is necessarily microscopic in size; it can be quite large, for example, several millimeters in steel. Still its length is smaller than when it ceases to depend on external stresses. In the language of mechanics this signifies that the length of the crack is smaller than the Griffith critical crack length, and for it to grow, more energy than the crack itself gives must be supplied.

Thus, a subcritical crack is stable, steady, even phlegmatic; in short — not dangerous.

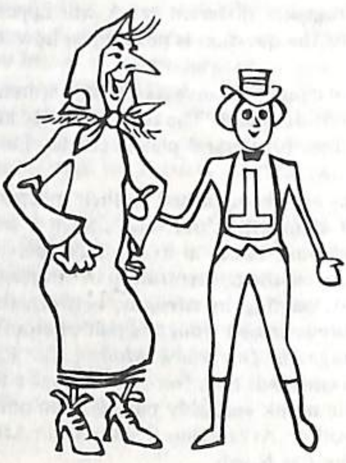
Sooner or later, however, this dormant state will come to an end and then an altogether different crack will appear — a beast of prey. That is why the question is posed: just how does such a crack grow?

This question cannot be answered in one sentence because there are different kinds of cracks. The reader already knows that cracks are subdivided into brittle and plastic cracks. Let us consider the first kind.

Brittle cracks are distinguished by their independence of plastic deformation. It claims this 'out loud'. Such a crack involves the rupture of interatomic bonds at its tip. First, between the first pair of atoms; then, after the concentration of stresses, between the second pair; then, gaining in strength, between the third pair. . . Thus this fracture is passed from one pair of atoms to another, like Chekhov's mirage in *The Black Monk* . . . "From one mirage another mirage emerged; then from this mirage a third one; so that the image of the monk endlessly passed from one layer of the atmosphere to another. At one time it was seen in Africa; at others, in Spain, India, the Far North . . .".



What have experiments shown? Unfortunately, nothing at all. The reason for this is that it is very difficult, although probably possible, to carry out an experiment absolutely free of plastic deformation. At the present time it is theoreticians who completely dominate in this field. And this is generally how they work. On a piece of paper they draw a crystal consisting of 100 or 1 000 atoms — a crystal lattice of ten atoms by ten atoms. They choose a law of



interaction between the atoms and plot a crack a few atoms long. Then with the aid of a computer they calculate how on applying an external stress the equilibrium of this imaginary crystal will be altered and how the crack will grow, i.e., break the interatomic bonds at its tip. Soviet scientists, and many in other countries, are working in this field. However, the results obtained are not very promising for at least two reasons. First of all very conditional atomic bonds are considered — actually they are immeasurably more complicated. Second of all, the crystal is much too small and computer memories are as yet unable to support larger ones. That is why the results obtained are not reliable.

Some of the results of this group of studies led to an astonishing conclusion. It appeared that in spite of the fact that there were no initial premises in any way associated with plasticity, calculations indicated that in the vicinity of the crack there appeared . . . a typical dislocation. Can it be that dislocations which, according to the rules of the game, should be absent in brittle fracture are present here?

A. N. Orlov and V. I. Vladimirov describe a mechanism of crack growth based on the existence of point defects in crystalline materials. The term itself — point defects — is employed in physics to denote two states. In the first one, an atom is extracted from its position of equilibrium by thermal oscillations. This means that in the process of thermal motion one of the atoms was simultaneously attacked by several of its nearest neighbors and flung into the interstitial space. Such an atom, having lost its long-occupied place in the crystal lattice, goes 'underground' and wanders like a vagrant in the crystal at a speed of up to 1 km/h. It is called the interstitial, or the Frenkel defect. J. Frenkel, as the reader probably knows, was an outstanding physicist who 'spilled' an avalanche of ideas, one of which was the idea of point defect. The second point defect, or the Schottky defect is the vacancy that remains after an atom passes from its settled state to a wandering one. The Schottky defect (vacancy or simply hole) is high-spirited and can move at a considerable speed — up to 10 km/h, i.e., many times faster than an interstitial. The reader may wonder how a vacancy moves. Very simply. Let us suppose that there is a vacancy at some lattice point. An atom from an adjacent point settles on it. Naturally a vacancy will appear in the place formerly occupied by that atom. Another atom moves into this vacancy — in this way the vacancy moves from one point to another, like the shadow of the atom that leaves

it. In this respect the crystal resembles a concert hall with unoccupied seats. If the concert is interesting, the spectators try to change their seats to ones nearer to the stage; the vacancies, the unoccupied seats, are farther and farther from the stage.

These two defects lead to the growth of microcracks. This is how it takes place. At the tip of a crack, due to the joint effect of thermal oscillations and an applied load an atom escapes into the interstice and slowly migrates to areas distant from the crack, moving in a zigzag manner like a particle in Brownian movement. This process is repeated many times, and in place of the atoms, vacant spaces form at the tip of the crack. This signifies that the crack has grown.

In case the growth of a crack is determined by vacancies, the final result is the same although the mechanism is different. Now streams of vacancies flow to the tip of the crack. They take the places of atoms at the mouth of the crack, ensuring its growth. The difference between the two processes is that the first one is accompanied by an increase in the density of interstitials in the vicinity of the growing crack, whereas this is not so in the vacancy mechanism, and, besides that, the second process proceeds at a much greater rate. But the result is the same. With the aid of point defects the crack is capable of subcritical growth. Since point defects are only active when the temperature is high enough, these mechanisms operate only when relatively low-melting materials are subjected to loading very slowly. Otherwise, elevated temperatures will be absolutely necessary. In general, this process is of a statistical nature. This means that within a microsecond the rate of outflow of interstitials from the tip of a crack and that of inflow of vacancies will pulsate, this being a process of diffusion. Just like in Lewis Carrol's *Alice in Wonderland:* "There was no 'One, two, three, and away!' but they began running when they liked, and left off when they liked, so that it was not easy to know when the race was over . . ." However, when the process goes on long enough it proceeds at an average, monotonous, measured rate.

Still these are not the main mechanisms. Physicists have found a great deal of evidence indicating that the subcritical growth of cracks is inseparably associated with plastic deformation. This is not accidental — plastic deformation not only accompanies and verily controls the process of crack growth in the early stages, but apparently serves as its principal driving force. This 'betrothal' of a subcritical crack to plastic deformation is clearly manifested in all the dislocation mechanisms of the 'maturing' of a crack.

For the growth of the crack they all require dislocation fields of that atmosphere without which a subcritical crack cannot 'breathe' — because it is still incapable of growing due to elastic stresses. Therefore a crack demands a considerable number of dislocations per unit area — about 10^{10} per cm^2. But this is not all. A crack is very selective and for its propagation it demands not simply any dislocations, but dislocations of like sign. Physicists say that one of the conditions for subcritical fracture is that the dislocations be dispersed in space so that in a given volume all (or almost all) the dislocations have the same sign. Is this not too complicated for a common 'vulgaris' crack?

The point is that the principal way dislocations act on a crack is through sacrifice — the dislocations pouring into the cavity of the fracture increase it; after which the dislocation itself vanishes. The resulting crack is located so that the vacancy brought by the dislocations lies along the base of the crack-wedge under the dislocation extra planes. That is why the sign of the dislocation makes a difference: a dislocation with a positive sign promotes the growth of a crack downwards; with a negative sign, upwards. It is clear that in order to assure steady growth of cracks, it is necessary that the dislocations be of like sign.

Do these mechanisms of growth of subcritical cracks have names? Yes, they do: the first one, the Orowan mechanism is based on an individual slip band approaching an already existing crack and feeding it with dislocations dumped into the crack. It appeared, however, that dislocations attacking from a single slip band were not enough. E. Parker sent into the crack packs of slips, i.e., systems consisting of a large number of parallel slip lines.

A. N. Orlov presented a more complicated picture; he considered the propagation of a subcritical crack near barriers retarding dislocations. This immediately led to the fitful propagation of cracks in the earliest stages of their existence. The 'disposition' of the microcracks is spoiled: they become disorderly, almost explosive and in this way have made the subcritical crack more dangerous.

But we must admit that Nature has helped us very much by providing cracks with a period of subcritical growth. Suppose it did not exist. At the present time without doubt there is always a great number of incipient microcracks in metals and in any crystal. Just the same materials possess a definite immunity to them; manage to

live with incipient microcracks and still fulfill their duty to structures, and, consequently, to mankind. The birth of cracks and their growth, therefore, are disturbing but not alarming. Why? Because these cracks are subcritical and in order to pass over to the dangerous state they must go through the slow process of subcritical development.

Thus, the subcritical period is a great boon for mankind; it is a delay in fracture that is granted us by Nature — time to save the structure from an accident.

'MATURITY' OF A CRACK — THE ACTIVE AND CREATIVE PERIOD

Everything took place in a moment . . .
(After L. Ozerov)

Our last words were almost optimistic. There seemed to be good grounds for this . . . the metal was not destroyed. And if the cracks existing in it or formed in the process of deformation were not so pleasant, yet they were not so terrible. The most we allowed ourselves was to pose a complaisant academic question:

What is there beyond this summer
in the world of THERE, in the land of THEN? . . .

(After R. Kazakova)

Nevertheless our mistake was rather a natural one.

All that took place during the birth of the crack and its slow subcritical growth was not only a preamble, but what is much worse, the basis for an approaching catastrophe.

As the subcritical crack grows, plastic deformation proceeds in the surrounding material and strengthens the metal. It is most active at the tip of the slowly, hesitatingly creeping crack. Besides, the process of formation of new cracks continues and the growth of the main one proceeds in a sea of small cracks. This introduces an entirely new process — the small cracks are devoured by the main crack which grows more rapidly. At times it minces along, swallow-

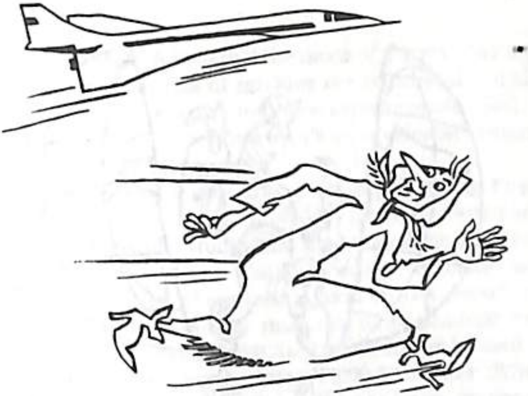
ing the dislocations at its tip; at other times it leaps ahead, swallowing other smaller cracks. Yet the rate of growth is still slow — merely a few millimeters an hour. The structure is still alive and seemingly healthy. But a stream of energy from its strained mass flows to the crack, causing irreversible deformation and preparing the metal for inevitable destruction. All this time the structure is resisting the external stresses and continuing to do its job.

But now the process has reached the stage when the metal surrounding the crack, due to plastic deformation, has reached its ultimate strength. This is 'beneficial' for the crack. First of all it now moves in the material together with a large number of dislocations of like sign. In the second place the crystalline grains of the material have begun to move like drifting blocks of ice — they turn around at the tip of the crack, presenting their vulnerable crystallographic surfaces to the attacking cracks. The number of tiny cracks has become so great that the main crack snatches them from the right and left, leaping vigorously from side to side. And although it is said that one door cannot be opened with two keys, in this case the door that protects the strength of the metal is opened by three keys simultaneously. All this indicates that the crack is approaching a critical situation.

Finally, the crack has grown to the Griffith length. This means that from this moment all the elastic energy coming from the strained structure is assimilated by the crack alone. An end has come to the previously active processes of deformation of the surrounding

area, the filling of it with dislocations, the turning of the grains, etc. If they still continue it is only at the very tip, and from being the main processes they have become secondary ones. Only a very small part of the elastic energy is enough to compensate for the more than modest 'plastic' appetite of the crack; the main flow of energy is spent on breaking interatomic bonds at the tip. Now the process either becomes truly brittle, or as physicists say, quasibrittle, i.e., seemingly brittle. This only emphasizes the fact that although plastic deformation continues to take place, it no longer plays a decisive role.

In the words of A. Blok ". . .The time has come. Misfortune flaps its wings . . ." The crack begins to pick up speed. It is difficult to imagine it, but it does so with an efficiency that can be envied by an air-defence rocket. The acceleration of the crack reaches 1×10^8 m/s^2, which is 10 million times the acceleration of gravity. This signifies, for instance, that in a thousandth of a second the crack can develop a speed of 3 km/s. In the flash of a moment, from a sluggish lout it has been converted to a sprinter whom it is hard to hold back, has flown over from the sphere of physics to that of pure mechanics and has carried us there with it. It is not so simple to break away from the familiar concepts of dislocations, vacancies and interstitials. This means returning to the everyday world of macroscopic phenomena and processes. This not only signifies an abrupt change in the scope but also in the direction of thought.



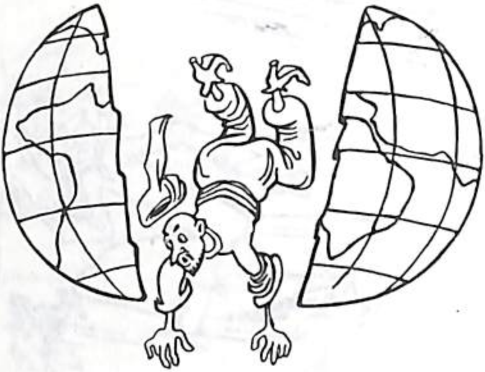
Finally, this means that it is absolutely necessary for us to see the romantic and vivid in dull mechanics.

. . . What seemed to have so little meaning,
to be so flat, so dull, so even, —
of a sudden shot up its towers and walls
and became the most important of all.
What seemed as boring as a textbook,
as completely dead as a dug-up bone, —
of a sudden became the foundation stone . . .

(After Ya. Belinsky)

In what is the supremacy of mechanics manifested in the last stage of supercritical fracture? First of all, in an indifference to structure. Steel, for example, consists of several constituents — ferrite, cementite, pearlite. A fast crack does not take any notice of this and cuts all the constituents indiscriminately. When the crack attains a sufficiently great speed of several kilometers per second, practically all known materials and substances become brittle. This is not surprising if we speak of steel, but even plexiglass, which is not especially brittle, cracks like a nut. Plexiglass is nothing: pour liquid oxygen into an ordinary galosh and it will break into strips of cloth-lined rubber.

You may object and say that intense cooling is required for this. Well yes, but the rubber will crack like glass even at room temperature. For this purpose it is only necessary to speed up the crack.



The first series of brilliant experiments was conducted before World War II by the Leningrad physicist M. I. Kornfeld. He shot a bullet into an ordinary jet of water and the bullet literally split the water. To be precise, it was not so much the bullet as cracks that spattered the water into fragments. Consequently, even a liquid can be split by cracks if a load is applied fast enough. Obviously, butter can also be cleaved by bullets and cracks. But you know that. Just recall how frozen butter breaks when cut with a dull knife. Thus, in mechanics the structure of a material is of secondary importance. Of greater importance are the macroscopic properties of a substance, such as its strength, ductility, modulus of elasticity (Young's modulus) and others. As far as dislocations and other defects are concerned, they retreat to the background. And then the fracture of widely different materials — metals, monocrystals, minerals, amorphous substances and . . . even liquids — takes place in accordance with general laws that clearly and plainly disregard the physical structure of a substance and are based only on its elastic characteristics.

Such is the nature of a crack. At its birth and during its slow growth it is governed by physics. But in the supercritical state it obeys the laws of mechanics.

The best proof that this is so is the ultimate speed of propagation of fast cracks. Almost all the theoretical calculations in this field have been conducted by physicists in various countries and they can be divided into several series. First of all Griffith's

classical investigations showed that the speed of a crack after it had lost its stability was capable of reaching the velocity of sound. It must be noted that this was not confirmed experimentally. Still, for all that a crack, that often destroys man's most valuable creations, has hardly become less disastrous.

The second series of investigations was begun by the English scientist Nevill Francis Mott, probably the only well-known physicist who successfully studied the supercritical stage of crack growth. He, and later Robert Wells and others, estimated more soberly the highest speed of cracks that have 'broken loose': they believe it to be equal to 0.38-0.40 times that of longitudinal sound waves. For steel, for example, it is 2 000-2 200 m/s, and for monocrystalline diamond even greater, 6 000-7 000 m/s. What a sprinter! And not only a sprinter but an extraordinary, unflagging long-distance runner.

The English writer G. Chesterton relates an ancient Moslem legend how a certain sultan once commanded his subjects to build a pagoda that would rise higher than the heavenly stars . . . but Allah struck the sultan with a bolt of thunder that made the ground gape under him and he was hurled downwards to infinity, his body boring a well that had no bottom, like the tower he conceived of without a top. And the arrogant soul of the sultan is eternally rushing down this tower turned upside down . . .

A crack can also maintain its velocity just as endlessly, if only the thing that is being destroyed is large enough and the flow of energy from within it or from the applied load continued while the crack propagated, no matter how long.

The third series of investigations appeared thanks to the original research of Elizabeth Ioffe from Great Britain. She showed that branching takes place at speeds of a crack equal to 0.6 the velocity of transverse elastic waves. This phenomenon, i.e., the speed corresponding to it, was taken by Ioffe to be the maximum possible speed of growth of the crack. Calculations subsequently made by others showed that the speed was equal to 0.53 to 0.794 times the velocity of transverse waves. For steel the speed of the crack is from 1 600 to 2 000 m/s, i.e., lower than the ultimate values according to Mott. The principal mistake in these investigations does not lie in an error of determination but rather in the fact that branching does not stop the propagation of a crack, but only opens a new door for fracture. It is such a door that after passing through it, the crack

can no longer be repaired. If in the case of fast but ordinary fracture a structure splits into two parts which can be somehow joined (for exa.nple, by welding), after branching the structure is converted into a heap of fragments. It is sometimes even hard to collect them.

. . . Thus nature creates and perfects
At times a most exquisite thing
Then in the flash of a moment begins
To destroy it and to fling
The fragments far and wide

(After C. G. Leopardi)

The fourth series of investigations identifies the maximum speed of crack propagation with that of Rayleigh waves. What waves are we alluding to? Unfortunately we are very familiar with them. When an earthquake occurs, at its source there originate elastic vibrations — longitudinal, transverse and surface vibrations. If the first two move in the body of the earth, the third propagates only along its surface. The points at the surface move in an ellipse. In general, they are the same waves that originate in water, but they are manifested in more varied ways. For example, surface waves can race along the bottom of the ocean, between two closely contacting masses. The main difference between them and longitudinal and transverse waves consists in the fact that surface waves attenuate very slowly. Longitudinal and transverse waves move within the volume of a body and therefore attenuate at a rate inversely proportional to the cube of the distance while the rate for surface waves is inversely proportional to the square of the distance. Therefore, as the distance increases, longitudinal and transverse waves leave the game, while surface waves remain and carry the destructive energy of the earthquake that occurred somewhere at the other end of the globe.

The maximum speed of cracks is associated with these waves. In steel the absolute velocities of Rayleigh waves reach about 3 000 m/s. G. I. Barenblatt believes that if a crack attained this ultimate value, a state of resonance would originate at which the crack irreversibly loses its energy, although it continues to receive energy systematically from the body being deformed. The crack behaves like a spendthrift or squanderer who spends much more than he receives. The author believes that the mechanism is a different one. The growing crack discharges energy accumulated in the body,

which flows into the cavity of the crack and is converted to surface waves. The latter convey the energy to the tip of the crack. If the tip of the crack is supplied with energy by surface waves, it would seem that there is no longer any doubt that the speed of a crack is connected with the velocity of Rayleigh waves. The only trouble is that a closed cycle of energy flow has not yet been proven directly, neither experimentally nor theoretically, although Rayleigh waves have been detected in the cavities of cracks.

What can experiments say about the speeds that a crack is capable of attaining? First of all, a crack does not attain its full speed at once. At first it picks up speed at a rate that increases with the load applied.

It can probably be considered an established fact that the speed of a crack is proportional to the flow of elastic energy to its tip. At this stage, therefore, the rate of fracture is determined by the conditions of the experiment: the stresses, the size of the specimen, the rate at which the external load is applied, and many other factors. It is a different matter when the crack attains full speed; in steel, for example, it varies from 2 000 to 2 600 m/s. Then velocity does not depend on the nature of the object under destruction and is determined only by its elastic properties. For instance, it is similar in steels of different compositions. Although the ductility of different steels varies considerably, this does not affect the velocity of sound in them. In the end, the maximum fracture speeds are fractions of the velocity of sound. No wonder then that a fast crack can reach the same ultimate speeds in mild steel and in high-carbon steel, and in hardened steel and even . . . in glass. The behavior of a crack at the critical speed ignores the individuality of materials and therefore arouses an inner protest in us. But nothing can be done about that. Such are the laws of Nature.

The highest speed of a crack is the one that reaches that of Rayleigh waves. To speed up the propagation of a crack to such a rhythm is difficult, but possible. The author was able to do so only in the case of pulse loading. A supply of energy from within the mass of the loaded specimen could not be relied upon. Therefore in the immediate vicinity of an incipient crack a small charge or explosive was set off. It was this energy that determined the growth of the crack in the first microseconds after the explosion. And both in glass and steel, for a short time the crack managed to attain a speed

of 3 000 m/s. Here verily, as was pointed out by a Swedish journalist, "At times thanks to a good kick, we acquire wings." When the wave arising at the site of the explosion overtakes the crack its rapid growth is retarded and the fracture propagates at Mott's rate of about 2 200-2 600 m/s.

Thus, it appears that the maximum speed of motion of a crack is actually associated with Rayleigh waves. This has been recently confirmed experimentally by L. M. Lezvinskaya and the author. It seems that the energy from the mass of the metal being fractured does not flow into the tip of the crack but, strange as it may seem, in the area in front of the crack. As the velocity grows, the flow of energy that supplies the crack is dispersed within an expanding area in front of its mouth. More and more energy 'misses' the tip and thus withdraws from fracture. At the maximum speed equal to that of Rayleigh waves, almost all the energy fails to get into the tip and escapes into space.

For a long time the concept of the Rayleigh barrier predominated. Still an opinion was advanced that if the tip of the crack were supplied with energy in some way at a speed exceeding that of Rayleigh waves, it would be possible to accelerate the formation of a crack and to attain super-Rayleigh velocities. But it would be hard to achieve this directly. In 1970 the investigations of a group of modern scientists produced a great sensation. They directed a light pulse of a ruby laser onto a potassium chloride crystal, converting the substance at the focus to plasm with a temperature of one million degrees, propagating at a rate of tens of kilometers per second. A crack appeared along the front of the plasm. The plasm penetrated into its cavity and formed something like a wedge which accelerated the crack. The rate of propagation was astonishing — 60 km/s, i.e., 10-15 times the velocity of sound. How did this become possible? First we must explain why this was previously impossible.

When we applied a load and extended the specimen, the crack received energy through an intermediary — through the material of the deformed metal which could at the best admit stress waves moving at the speed of sound. In the case of a laser, the energy of the plasm is applied directly to the tip of the crack. The absence of an intermediary makes it possible to pour in energy at an unlimited rate, thus speeding up the crack, as shown by calculations, 25 times swifter than the speed of sound. Of interest is the fact that the

material in front of the wedge is not alerted to the advance of the crack until it is directly subjected to impact. We are not speaking about ordinary fracture but of the ultrasonic flow of solid substances surrounding the hot plasm and crack.

That could be the end of this section. But I would like to share with the reader the feeling that filled me many years ago when I first started working. Every time my motion-picture camera (a fine reliable device) presented new and new figures of astonishingly rapid fracture; every time I read papers about the mad speeds of cracks, the thought used to occur to me that there couldn't be many forces capable of stopping this triumph of insanity and chaos. As a matter of fact, however, scientists in various countries had already laid a strong foundation beneath the science of strong materials.

'PRINCIPLES' OF A CRACK

There is nothing . . .
The urge to run, to move
That is the essence
Of everything . . .

(After M. Eminescu)

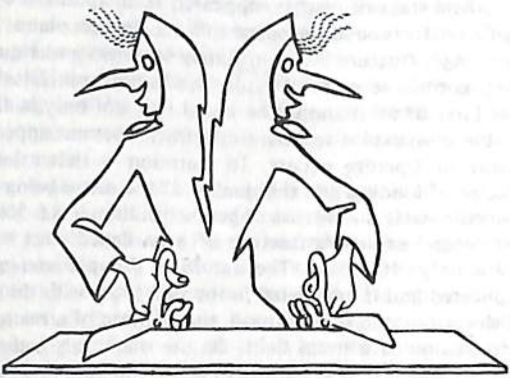
All that has been said above has shown that structures with cracks seem to be doomed; that evil, I would say, triumphs. The supercritical stage of fracture appeared as an apothesis of insanity, bringing misfortune at the speed of a modern jet plane. Indeed, in its last stage, fracture is astonishingly senseless and headstrong.

Let us observe more carefully the 'moral principles' of a fast crack. First of all it should be noted that not only in the case of slow, but even explosive fracture, a crack does not appear at once. A delay in fracture occurs. Its duration is determined by the character of loading and the quality of the metal being fractured. For ductile steels, in the case of gentle bending, it is 6 500 μs. In the very 'savage' explosive fracture of a hardened steel strip — the delay is only 10-15 μs. The nature of this phenomenon is very complicated and is associated in the first place with the generation of dislocations and their motion, the creation of a microcrack and the formation of a stress field. On the whole this is the period of 'birth' of fracture. It is natural to ask if this first stage in any way

affects the subsequent propagation of the crack. It does not. The 'principles' of a crack are rather simple — it lives in the present, moving in the direction and manner demanded by the stress field at a given point in space and time. It does not remember its past. This is not an uncommon phenomenon in physics. For instance, when somewhere in space, waves of any nature whatever are imposed on one another and interact, they move ahead as if no interaction has ever taken place between them. There is even a special principle of superposition, which determines this phenomenon. This principle states that in any complicated acoustic process, each wave, each sound, maintains its sovereignty and can always be isolated, although not without cunning. As E. M. Remarque says in his book *Shadows in Heaven*, "It is like wind and water; they move each other but each remains itself."

A crack grows in the flow of attacking elastic waves. The waves submit to the principle of superposition and force the crack to submit, also. Hence, at each moment in its movement the crack behaves like someone who 'does not remember his kinship'. Its behavior stems only from the actual situation of the stress field at the given moment. It is practically free of inertia and 'conscience'.

The incredible sensitivity of a crack to local changes in the elastic field leads to a complicated phenomenon called branching. It manifests itself quite simply. At high enough speeds, in steel up to 1 600-2 000 m/s, a crack divides into two or three. Each of the resulting cracks can propagate further and likewise branch out.



However, after each act of branching the crack loses speed, which sometimes reduces to zero. Then there follows rapid acceleration up to the threshold speed, branching, and again a drop in speed.

Why does this take place? Because the elastic energy consumed in brittle fracture is spent on compensating for the surface energy. Whereas in ordinary fracture two surfaces appear, as a result of branching into two cracks four surfaces appear; and in case the crack branches into three, six surfaces. Therefore, the store of elastic energy in microvolumes of the material adjacent to the crack is quickly exhausted and the speed of the crack decelerates or the crack even comes to a stop. Some time is needed for elastic waves to bring new stores of energy from afar. The number of such cycles is unlimited because due to enormous acceleration, the velocity of the crack grows with lightning speed and for a distance of a few millimeters it is capable of branching many times.

The birth of secondary cracks is always accompanied by curvature of the trajectory of the main crack. The sequence of events is as follows. At first the main crack turns aside, forms a branch, and then returns to its former path. As a result, the branch is directed at a tangent to the curved part of the path. Subsequently the secondary crack is deflected at an angle of 30-40°.

Thus, the formation of a secondary crack is connected with curving the main crack. Their subsequent divergence is due, probably, to deflection in accordance with the law of conservation of the amount of movement. Nevertheless, even in the case of many branches, the main crack propagates relatively rectilinearly. Therefore, curving of the crack due to its instability is primary, while branching is secondary. Elizabeth Ioffe showed that branching must ensue when in the wide area in front of a fast crack approximately equal stresses arise and it makes no difference to the crack which way it goes. In this case the crack can easily 'lose its way' and deviate. Under these conditions the branching off of a crack favors rectification of the path. This somehow resembles jet propulsion when the substance ejected from the rocket can impart to it motion in the opposite direction.

In the preceding section we have said that branching opens a new door for fracture, a new page.

This is quite an unusual process. At times branches can turn 90° with respect to the main crack, and even move in a direction opposite to the crack. This is often observed in the case of explosive

loading. It sometimes happens that the crack even grows along a tensile stress, which is most rare. It is true that in this case it keeps twisting along the direction of the applied force.

The processes taking place along the front of the crack are no less complicated. Under ordinary conditions it slopes gently. That is, the crack advances on the material approximately equally throughout its cross section. It is different in the case of branching. When it sets in, the crack attacks the metal plate with two columns. The front is split and has the shape of two petals on the surface. At the critical speed, both of these cracks on opposite sides of the specimen attain considerable independence, allowing them to roam from side to side and produce new branches. They are extremely sensitive. They react to the smallest changes in the elastic field or in the structure of the material.

In hardened high-carbon steel, branching sometimes assumes the most unusual shapes. It cuts the mass of the metal into many large fragments. Besides that, a great number of tiny fragments sometimes hundredths and thousandths of a millimeter in cross section fall out from the surface of fracture. These fragments are chipped off from the material by the vibrating parts of the front of the branching crack.

It appears that this variety of microscopic whiskers is encountered when various monocrystals are fractured and they are, by far, not always associated with branching. However, in the process of branching, chips are formed on a mass scale and whiskers of the smallest dimensions can appear, even small crystals of needle-like martensite — the finest structural elements of hardened steel 10^{-4}-10^{-5} cm in cross section. This process of vibration of the front of a crack, in which either or both of the surface crack-petals give off branches, constitutes the mechanism of this phenomenon. Yes, its mechanism but not its heart!

There is as yet no agreement of opinion as to the true reasons for branching. Chronologically the first point of view is that of Elizabeth Ioffe who, as we know, associated the beginning of branching with threshold speeds. There is also another point of view that suggests branching starts when the stresses at the tip of a growing crack reach certain critical values. This however is not always confirmed. For example, in some steels there may be fast cracks and the stresses at their mouth may be very great, yet branching does not occur. In general, only in certain materials, not in just any one, do cracks branch: in hardened steels they do, but in heat-treated steel a crack remains unbranched at all velocities.

And what about hardened glass? The reader knows very well what happens to it when it breaks. It is sufficient to picture what occurs when a stone hits the front glass of an automobile. Cracks radiate from the spot of impact; also, all the sectors between them are split by transverse cracks. Both kinds of cracks propagate at a speed of 1 500-1 700 m/s and in a moment convert the large and solid glass into a heap of thousands of tiny fragments . . .

No wonder during the war strips of paper were glued crosswise on window panes. At the present time triplex (laminated safety glass) is used in automobiles for this purpose. Two of its layers consist of hardened glass, while the third layer (between the other two) is a ductile plastic that keeps the glass from breaking into pieces when it is hit.

Great velocities, evidently, are far from being a sufficient criterion on which to judge whether or not branching can take place. Take note readers, that the branching of cracks occurs in materials under considerable internal stress. Celluloid, plexiglass and certain other plastics are exceptions. In materials not under tension branching does not occur.

Branching should be associated with the magnitude and distribution of residual stresses in the material that is fractured. The following mechanism can be pictured. A quickly moving crack discharges residual stresses in its vicinity. Elastic pulses from the field of disintegrating internal stresses, brought arbitrarily to the crack, upset its regular motion. Under the effect of these pulses separate parts of the front cut into the faces of the crack, producing branching.

The Soviet writers Ilf and Petrov wrote that there was a watchman in the establishment, who strictly demanded a pass and if you failed to present one, he let you pass anyhow. Recently it has been found that, in principle, a field of internal stresses is not needed. In some materials, in particular metals, branching could take place once, providing plastic deformation is suppressed and the state of stress at the tip of the crack is increased. Thus, internal stresses are, apparently, stimulators, but not the initial cause of branching, which should be considered the instability of the crack, setting in when it reaches the critical speed.

These are the theoretical views concerning the nature of branching . . . interesting from the scientific point of view, but repellent from the practical one, i.e., that of the engineer. This is quite natural. If ordinary fracture leaves us some hope, branching disperses it figuratively and literally.

In discord fierce
both so ruthless,
So avidly fatal,
so rabidly sanguinary,
Oh brothers-enemies,
oh eternal antagonists!

(After Ch. Baudelaire)

Often fracture results from the growth of a single crack. But just as often a system of microcracks originates, which then unite by rupturing the ties between them. Sometimes a crack that seems to be a single one is actually a group of microscopic cracks arranged along and across the direction of fracture. Experiments show that for most materials there is actually a system of cracks, whereas a single crack can be regarded as a well-known and convenient theoretical approximation. This is not at all remarkable. Microcracks originate due to dislocations which are located all over the metal. That is why microcracks are generated over a large area of plastically deformed material. They were observed in polycrystalline steels, metallic monocrystals, in haloid crystals, in celluloid and plexiglass, to say nothing of glass whose production entails complicated processing that inevitably gives rise to the formation of systems of microscopic discontinuity.

Textbooks and Heaven only are ideal.
Solidity is an imperfect state.
Within the cracked and dislocated Real
Nonstoichometric crystals dominate.

John Updike, *The Dance of the Solids*

The reader himself, of course, has encountered such a 'crowd' of cracks. For example, you want to break a thin layer of transparent plastic. If it is sufficiently ductile, on bending it with some force you will notice at once that the material where it is bent has become cloudy. That results from the formation of a great number of cracks that disperse the light. When we bend a thin layer of polished aluminium, its surface also becomes cloudy. This is caused primarily by the complex topography formed on it due to the emergence of slip bands. Later, however, minute cracks appear in these bands, which in the end break the metal.

The number of examples can easily be increased. It is clear, however, that the formation of systems of microcracks prior to and during fracture is not an exception but rather the rule. This is good grounds for believing that any elastic medium being fractured should be regarded as a body containing numerous small sharp-edged cracks of various orientation.

Any metal from which planes, automobiles or ships are made is not, in the strict sense, a monolithic material. After treatment in a rolling mill, on machines, and in presses it has accumulated an enormous number of tiny cracks in memory of the various tools it has 'met'.

Such surprises, of course, cannot bring joy to strength experts. But what can we do about it? Not accidentally is it said that if you drive Nature out of the door, it will enter through the window.

Thus, always, or almost always, in real life metals work with previously contained microcracks or those that appear in the very first stages of deformation. The thing that is of the greatest interest is how and when the subcritical elastic growth of the cracks will come to an end and the second, uncontrollable and catastrophic stage of their avalanche-like growth will set in. The physical processes involved in such a transition in systems of cracks are not, as yet, quite clear. We are not alluding to the stability of one crack but

to that of a great number of them. All the more, it is not clear in microscopic conditions when one microcrack grows by devouring many others. Yes, I mean what I said. Cracks are beasts of prey, rather like cannibals that eat their own kind.

The battle between cracks is a battle of twins. Which one of the hundreds and thousands of cracks will be a conqueror and which a victim? Any of them can be one or the other. It all depends on its orientation and to what extent it has grown. The cruelest cannibal is usually the largest crack and one that is perpendicular to the tensile stresses. That is the one that moves ahead, probing the surrounding space with its elastic field. We do not have in mind a radar at its disposal. Simply it is very sensitive to the surrounding stress field. And the microcracks in its vicinity alter it, forcing the main one to become aware of it and to react by the motion of its tip.

As long as the distance between two cracks is much greater than their length, they are not aware of each other. But if the distance between their tips is less than the length of one of the cracks, the picture is different. Both of them being in a plastic material, let's say, mild steel, begin to turn their tips towards each other. This happens in the case of slow static loading and of dynamic loading. In the second case the rate at which the ties between the cracks are ruptured reaches 50 m/s. On uniting, the length of the main crack increases abruptly. The elastic field of such a crack becomes larger and the latter begins to be aware of cracks that are located farther away from it. Then there follows the 'bloody' act of devouring and the field becomes even more powerful. The devoured cracks are not always located strictly in line with the main one. Because of that its shape is complex, step-like. Then by uniting tens and thousands of its own sisters, the main crack at last attains the critical size. It can now disregard the plastic flow at its tip and the process of combining cracks is sped up. The rates at which the crack propagates and the ties between them are ruptured equal hundreds and thousands of meters per second. The character of the process is invariably wolfish, although the mechanisms of the loss of equilibrium can be quite different. For example, small cracks near the mouth of the main crack, that resemble pilot-fish at the mouths of some kinds of sharks, are now stimulated by the powerful elastic field of the main crack and unite with it of their own accord, forming a rapidly growing whole.

It is quite clear that this is already a misfortune. After the crack has begun to grow impetuously, devouring all the small cracks in its

path, the structure has no future. It is doomed. Of practical interest is the period of subcritical, stable existence of the metal, let there be a crack or a whole system of cracks in it. Nevertheless, the metal is obliged to work, to resist external forces, to do its job. It must live. And as a matter of fact we know that it does live. All structures, parts and units, without exception, contain cracks, and lots of them, yet they serve Mighty Strength! Why?

For two reasons. The first one is that they are designed so that the loads applied to them are always less than those necessary for the growth of the most 'aggressive' crack. The second reason is (we have already spoken about it) that metals are immune to cracks. This is achieved by 'vaccination' through plastic deformation. It postpones the supercritical process and favors localization of fracture near the most sharp-edged cracks and defects. Plastic deformation, like a person allaying possible conflict by tact and gentleness, reduces the field of elastic stresses at the tip of the crack, and not allowing it to grow, spends the accumulated energy on the motion of dislocations. It is too bad if the metal is brittle. Even if it were strong that would not save it from fracture should a stress concentrator or microscopic crack appear in it. Now that there is no shock absorber, plasticity, and the concentration of stresses in a sharp concentrator is so great that it will easily surpass the initial strength of the metal.

That is why it is said that high-strength steels are always more sensitive to cuts than low-strength steels.

Can metal with a subcritical system of cracks live long? Perhaps, even forever? That would be too good to be true!

Here too Nature took care to oppose minuses with pluses. One of the minuses consists in the following. Suppose that the load applied to a given part is small, incommensurably less than the ultimate strength. According to all the laws of mechanics, under these conditions cracks should not grow. But the Soviet physicist S. N. Zhurkov has proved that even in this case fracture is inevitable. The only question is — when will it occur? The bigger the applied load, the more inevitable is the end, and the earlier it will come. This is what is called strength-time dependence.

What are the physical processes associated with the reduction of strength with time? Evidently, there are many of them. There are dislocation phenomena in the case of crystalline materials. There is the growth of cracks due to vacancies and interstitials. There, according to some physicists, atomic bonds are broken. And, without

doubt, fracture proceeds as a result of slow subcritical merging of cracks. In general, however, this phenomenon as a whole is exceptionally complicated and has not as yet been investigated to the end. The main thing though is that even in the case of relatively low loads, no material can remain strong indefinitely.

What should we do? First of all we must strive to keep the number of microcracks in metals at a minimum. It is also essential that, since they do exist, they should be as small as possible. It is absolutely necessary to provide a buffer mechanism for retarding cracks. The simplest one, of course, is plastic deformation. Therefore it is desirable that the metal be as ductile as possible without loss of strength. If the above conditions are observed, even metals with many microcracks can serve people for a very long time, retaining their reliability and strength.

COLORATURA SOPRANO

It is as if
On splitting up
Small particles
Of matter
Do crackle!

(After L. Martynov)

The French poet Despréaux once wrote:

. . . Like a snake the crack does creep
Inaudibly along the wall
In the spacious hall . . .

Is he right? Does a crack creep inaudibly? The fact is that a crack is not silent. At every stage of its existence — from its birth to its fast supercritical growth — it continually lets us know about itself at the top of its voice. Doing so it 'broadcasts' in almost all the ranges of sound — from inaudible infrasounds, through the whole audible acoustical spectrum, to ultrasounds, also inaudible for us.

What is the talkativeness of a crack connected with? First of all, not only cracks are involved. Any body in which elastic waves propagate under the effect of an external load is capable of vibrating.

And since in each body the frequency of vibration is peculiar to it alone (its resonance frequency) during loading, especially dynamic loading, waves are radiated into the surrounding space long before fracture sets in. For instance, strike an empty pail or barrel; snap your finger so that its nail hits against a thin glass and you will hear the sounds it emits. Recall how when buying a cut-glass vase or bowl it is checked by the salesman. He taps it with a pencil or small spoon. If it is unbroken it will emit a clear ringing sound; but if there is a crack in it, a rattling sound will be produced. This is how the Soviet writer G. Semenov describes the sounds emitted by cut glass: ". . . he liked to demonstrate his skill to his household: he passed a stiff finger wetted in wine, or if there was no wine, in vinegar, along the rim of a bowl as if it were a string of a musical instrument, and at some moment or other there suddenly emerged the thin, sad, silver voice of fine crystal glass, which imperiously floated in the room and quietly died away, calling forth a triumphant smile on the face of Demyan Nikolaevich. The sounds were purer and richer than those of a cello or violin and it seemed that it was not the cut glass that emitted the sounds of ringing or the long-drawn humming of a wind, but that the air itself became full of rich singing. . . On seeing a new bowl he would say excitedly, 'You know, it sings like a bullfinch . . . What a ringing sound!' . . ."

The sounds described by G. Semenov are produced by friction due to rubbing one's finger along the rim of the bowl, exciting self-oscillation of the cut glass. Roughly speaking, the finger 'draws' a section of the surface until the elastic forces of the material exceed the frictional forces between the cut glass and the finger. Then contact is broken and the material of the bowl, being set free, moves rapidly, returning to its place. This process repeated many times is what produces the sounds. On applying a mechanical force to a part or structure, these and many other kinds of elastic vibrations are excited in them. That is why even in the earliest stages of purely elastic deformation, the metal emits sounds that, though faint, can be clearly heard.

Well, the elastic stage is over and plastic deformation sets in. The 'cry' of tin, already familiar in ancient times, is heard every time this metal is deformed. All metals produce a noise when deformed, although not such a loud one. For example, low-carbon steel under tension radiates waves in the wide temperature range of $+200$ to $-196°C$. The sound emitted by stainless and other steels depends on the degree of deformation. The sound is more in-

tense in the first stages of deformation. Polycrystalline zinc in the process of deformation emits, in addition to sounds of audible frequencies, inaudible ultrasounds of a frequency up to a million vibrations per second (herz). The intensity of the sounds emitted by all metals increases with an increase in the rate of deformation.

Practically every kind of deformation — tension, fatigue, creep — evokes sounds in metal: but the sounds are always faint, therefore special sensitive instruments are needed to register the waves that originate. Most materials produce a sound only while being deformed. But some are not silent even after the force stops acting on them. What can this be attributed to? It seems as if nothing is happening, yet the metal is troubled by something.

Because fracture shows no outward signs of complexity this does not mean that the process is a simple one. At the root of acoustic radiation of metals lies the movement of defects — of dislocations, twins and others.

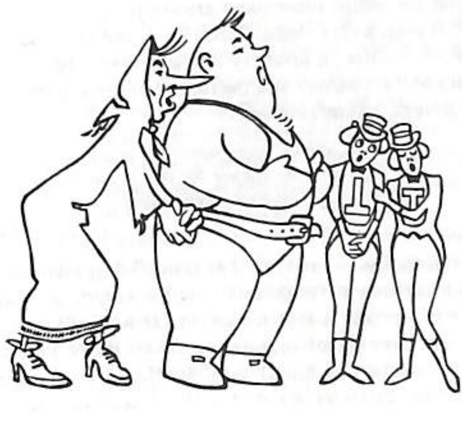
The outburst of high-frequency vibrations in the form of a great number of pulses that last from one to three billionths of a second (nanoseconds) occurs in the earliest stages of plastic deformation in all monocrystals that have been investigated. This emission of waves is connected with the dislocation slip that takes place at a rather high speed — 20 m/s. The sensitivity of available instruments allows us to detect the radiation of a single dislocaion or a small number of them, provided that the length of the dislocation area is not less than 8 μm.

Acoustic signals are emitted by a dislocation in several ways. A dislocation line propagating in a crystal can get stuck in it, hooking on to some barrier; but as the stress is increased, it breaks away from it. Then about a million segments fastened between the 'nails' in the crystal lattice break away simultaneously and produce a sound that lasts 10-30 μs. The Soviet physicist V. D. Natsik has showed that sound can be produced by a dislocation breaking through diverse barriers in a crystal. The point is that on passing through a barrier the dislocation has to reconstruct its elastic field. As a result, parts of this field 'break away' from the dislocation and propagate in the crystal in the form of a sound. It appears that the dislocations coming out on the surface of the crystal are also very noisy. There are two reasons for this. The first is that in this case the dislocation vanishes and the energy of its elastic field is converted to sound. The second is that the emergence of the

dislocation on the surface and the release of energy when it vanishes excites vibrations of atoms at the surface itself.

Twin bands are also capable of producing a noise, especially when they move near the surface of the crystal. Other defects of the crystal lattice are also not exceptions in this sense. To sum up the aforesaid, it can be said that plastic deformation, especially in the early transitional stages gives rise to an 'echo', a process that is the richer and more diverse, the greater the rate of deformation and the greater the number of mechanisms that accompany this phenomenon. Thus, every act of plastic deformation has its own sound, its own 'name and surname' expressed in the number of sounds emitted and their frequency. In the end it is determined by how one or another defect alters the elastic field and how fast it does so. The range of sounds depends on all this and can reach the region of ultrasounds of a frequency of several million herz.

If defects are compared to singers, then it can be said that the most 'talented' one is a crack: its voice is, perhaps, the richest one. The point is that a voice is determined primarily by two factors — its range and timbre. The voice of a singer, for example, varies in the range of about from 80 to 350 Hz (bass) and from 250 to 1 300 Hz (coloratura soprano). The timbre of a voice is the result of the summation of the main frequencies of a voice (tone) and additional vibrations of greater frequency (overtones), that distinguish one voice from another.



Sounds deprived of timbre, ornament, and arrangement are unpleasant to man and are not accepted as music by him. Apparently we are always drawn to a harmony of sounds, reflecting the fantastic diversity of the world surrounding us — its boundlessness in space and time, in ourselves and in . . . frequency.

Among the things in inanimate nature that are capable of emitting sounds, a crack, probably, has the highest 'voice'. This is due to the fact that fracture is a process in which elastic and plastic deformation occur simultaneously; their complex combinations occur at the birth of a crack, during its growth and after rupture. Naturally all the stages are accompanied by a complex interaction of wave processes.

I believe that if the frequency of the sounds emitted by a crack were lower its 'song' would be truly melodious. It would hardly be in the rhythm of an Ogiński polonaise; most probably it would be more modern, something like pop-music. Still . . .

However, let's get back to earth. It is impossible to hear the song of a crack because basically it lies in the range of ultrasounds. Hence, the name of this section is inaccurate . . . a crack 'sings' in a range much higher than a coloratura soprano.

Let us now talk about some of the types of elastic waves connected with fracture. To begin with, in most cases the appearance of a crack is preceded by plastic deformation which as we know radiates vibrations of high frequency and very low intensity. This accompanies the entire subsequent growth of the crack if along its faces there is even a very slight plastic flow. But now the first crack has appeared; it utters a loud cry like a newborn baby. Therefore the intensity and frequency and the timbre of the sounds emitted by the metal change instantaneously:

. . . And we must understand this as a signal
Sent to us by Nature for the reason
That it has entered a new season . . .

(After N. Zabolotsky)

The difference is so striking that acoustics in this case become an excellent instrument for determining the very first stages of the appearance of cracks. It is true that so far it is still impossible to determine the moment of origination of an incipient microcrack that is from two to five hundred-millionths of a centimeter, i.e., two interatomic distances in size; but that is a matter of technique.

It can be expected that this problem will be solved in the near future.

In the next subcritical period of growth of the crack, rather faint sounds are produced — only a whisper. There are outbursts of sound only at the moments when new cracks appear or cracks unite. On growing, the crack gradually gains strength and on attaining the Griffith critical length begins to talk, rather to shout in a loud voice. It manages to 'broadcast' sounds not only in the vocal range of 3 to 25 kHz, but covers the ultrasonic frequencies as well. And whereas energy is mainly spent on waves of a frequency of from 200 to 500 kHz, the complete spectrum goes beyond the frequency of 1 MHz. There is no doubt whatever that as the methods for measuring frequencies are improved, it will turn out that ultrasounds are not the limit. Apparently, a crack is capable of much more and can attain the hypersonic range. And that means heat vibrations of the crystal lattice, and their frequency is 10^9 to 10^{12}-10^{13}Hz. There are already strong indications of this now. Even before the war a group of German acoustic specialists detected circular grooves on the surface of fractured crystals. They proved to be formed by the propagation of Walner waves in the cavities of the crack. The waves were named after the physicist who had discovered them. The front of a crack on interacting with these waves deflects and forms grooves and steps. The frequency of these waves is equal to 10^{10}-10^{11} Hz. That's a coloratura soprano for you!

We can only envy the variety of genres in which a crack performs. Whereas a singer only makes use of longitudinal acoustic waves (air does not allow other waves to pass), a crack 'performing' in a solid medium 'sings' on longitudinal and transverse waves. Besides, it contrives to sing a solo on surface waves. It is true, though, that this solo is quite unusual — the waves move only along the surface of the crack itself. If the crack is an internal one, i.e., closed, the waves roll from one tip of a crack to another. So to say, a concert for its own pleasure. If the crack is open, the waves come out on the surface of the metal.[1] They were first observed by the author and also by I. S. Guz. The frequency of these waves proved to be up to 200 kHz and their maximum intensity corresponds to a frequency of 50-60 kHz.

---

[1]It is of interest that such waves can probably be found in singers since the body is a continuous medium!

As regards all waves connected with fracture, it can be said that their energy increases with an increase in the applied force and the energy of deformation. Heat treatment also affects the 'noise' emitted by steel. However, this does not take place directly but through a change in the properties of the metal itself.

But, finally, the last moment has come — the crack has traversed the cross section of the metal part and has run 'headlong' outside. And 'headlong' it is, because, the crack vanishes and instead of one piece of metal we now have two. But let us recall what the state of the metal on both sides of the former crack is. Both sides are naturally deformed by the applied forces. After fracture has taken place the resistance of the metal disappears and, consequently, the external force also disappears. And then the metal, left to itself, begins to restore its shape. If it has been bent, it straightens out; if it has been compressed it expands. It is here that powerful vibrations arise, leading to the propagation of a sound wave. Since the structure now plays the part of a torn string its frequencies are moderate; the acoustic spectrum accompanying fracture, as a rule, is concentrated in the range of audible and initially ultrasonic frequencies. But they are very powerful since the entire piece of liberated metal vibrates in a common rhythm!

The sounds of fracture are always individual and specific for a given process of rupture in a solid body. No wonder it is so, because

the sounds emitted constitute a picture drawn in sounds of the structural characteristics and deformation, of the birth of a crack and the supercritical rupture of the material. Therefore, a careful analysis of the sound spectrum tells us much, if not all, about what has occurred and is occurring in the process of fracture. It is not a simple matter, however. At the present time it is still impossible to get a complete picture of the mechanical processes through the sound spectrum because of our limited knowledge and because we still cannot hear the echo of every physical process. But this problem will undoubtedly be solved in the near future. Meanwhile, even now, we do understand some things. We can ascertain, for example, by the intensity of the sounds whether there is one crack or a hundred. The echo of ordinary fracture can clearly be distinguished from that heard in the case of the branching out of cracks. Branching has several specific features. First of all the growth of an ordinary crack is relatively monotonous, whereas in the case of branching it is spasmodic, interrupted by the birth of newly branched cracks. Besides, in branching a 'whisk broom' can originate from a single crack. Recall how in hardened glass hundreds of cracks diverge like lava in streams that are crossed by other circular cracks.

All this diversity of sounds emitted by materials is projected onto our devices. An analysis of the data obtained shows that in hardened steel the birth and speeding up of a crack prior to branching is accompanied by relatively low-frequency elastic pulses (40-50 kHz). Unusual acoustic signals begin to appear after the crack attains a speed of propagation of 1 900-2 200 m/s, i.e., when branching sets in. In the spectrum of the crack there appears a high-frequency component consisting of pulses that last 0.5-2.0 μs. Each pulse is a visiting card of the branching process. Branching in hardened glass lasts about the same time — 1 μs. In general, the acoustic signal of the process of branching as a whole is much more powerful than that in the case of ordinary fracture, and it clearly denotes the origination of branches — because the growth of a single crack is like the chirp of a bird compared to the rumble of an earthquake that is emitted in branching.

By the way, it should be mentioned that the reflection of cracking by sounds is not the only way in which discontinuity manifests itself. For example, discontinuity in some crystals is accompanied by various kinds of luminescence in the form of pulses that last 1 μs.

In the fracture of crystals, both faces of the crack are electrified, i.e., covered with unlike electric charges. An ordinary capacitor is produced. As the crack grows, its faces draw apart, which in the language of electrical engineering signifies an increase in potential. As the latter grows, there is a breakdown in the intermediate space. In other words, a discharge arises, accompanied by electromagnetic radiation and flashes of light.

In addition to these phenomena, the opening crack emits a flow of electrons; and not ordinary ones, but accelerated electrons of a voltage up to 15-40 kV. Where did this voltage come from? It could only arise from the charges in the cavities of the crack. It appears then that the charges are considerable. They are particularly on the surfaces of the crack and at its tip.

While growing, a crack is capable of producing another effect — the emission of electromagnetic pulses that last microseconds, and are repeated every few milliseconds. The peculiar feature of these phenomena is that they not only arise during the growth of the crack, but also after fracture. This is not surprising because the electrical processes on which they are based continue after the faces of the crack are separated; they are still sensitive to each other even at considerable distances.

Well, that is what a crack, the singer, is like. It performs in the range of audible sounds and in the language of ultra- and hypersounds. But that is not enough for it — it sings in electromagnetic and 'electronic' dialects and even . . . in the jargon of light! A very excellent performer indeed! And to all appearances this is still not its limit!

SUCH IS THE NATURE OF THINGS

. . . Eager to behold and unite as a whole
All that is already known to your mind.

(After Irakli Abashidze)

Let us summarize this chapter. First of all we have come to know that fracture is not an accidental process. It is predestinated by Nature itself. This is perhaps one of the manifestations of the Second Law of Thermodynamics, according to which every physical system left to itself will sooner or later decay.

If it is a fire, it will go out and the temperature will be equalized. If it is an accumulation of matter, it will turn to dust and be scat-

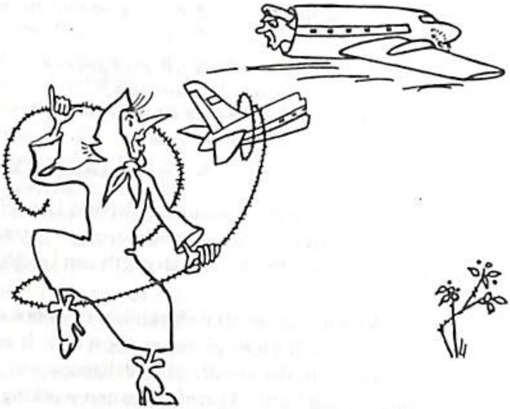
tered into the surrounding space. If it is a living organism, sooner or later, it will die.

> *. . . When I have seen by Time's fell hand defaced*
> *The rich proud cost of outworn buried age;*
> *When sometime lofty towers I see down-razed*
> *And brass eternal slave to mortal rage . . .*
>
> William Shakespeare, *Sonnet 64*

A crack, probably, is an implement of the Second Law of Thermodynamics. All our experience indicates that strength is transient, and even metal possessing the theoretical strength can be destroyed by external forces.

This, of course, does not mean that durability does not exist at all and that any structure will go to pieces as soon as it is created. Even a living organism, up to the middle of its existence, successfully fights against the 'Second Law'. Therefore, when working on the problem of strength we must be optimistic and understand that much is in our own hands. We can postpone any of the mechanisms of fracture to a later time. We are capahle of hindering the processes that underlie fracture. That is why in order to be able to fight them, and if necessary to utilize them to our own advantage, we must have a good idea of what fracture is all about.

So what is fracture all about? It is the death of a material or a structure as a whole, which is begun first of all by elastic deformation that occurs when static or dynamic loads are applied to it. In the latter case it consists in the propagation of elastic waves in the material. Then follows plastic deformation accompanied by irreversible structural changes. This is accomplished by the motion of dislocations in crystallographic planes. On interacting with one another the dislocations are capable of forming microcracks. That, properly speaking, is where fracture begins. Microcracks may grow slowly and this stage can last for years. This is the period of subcritical growth of the crack when the structure still retains its ability to resist external stress. It is like living with a malignant tumor which for some reason has stopped growing . . . But now the barrier has been crossed and the size of the crack exceeds the critical length. The energy contained in the volume under stress flows over into it, easily compensating for the energy spent on plastic deformation and vigorously driving the crack ahead. Now the life of the metal is reckoned not in minutes, and not even in seconds, but in milli- and microseconds as the crack propagates at a rate of many kilometers per second. The metal is doomed.



Metal, the polyglot, monolithic at the beginning and then disintegrating, speaking in the languages of sound, light and electromagnetic waves, tells us about its state all this time — from elastic deformation to complete failure.

Such is a brief description of fracture. Modulating it, the Polish writer A. Minkowski picturesquely describes the death of a tree in his book *The Roads of Memory*:

". . . I saw how a tree was killed: from one side of it a deep cut is made with an ax; from the other, it is sawed by two persons. At first nothing remarkable happens. The enormous pine tree, suspecting nothing, continues to stand calmly, spreading out its needled twigs. Suddenly a shiver passes through it from end to end. A slight trembling is followed by the troubled noises of the branches. Then the unruffled calm is disturbed only by the rhythmical whining of the saw. This is followed by the faint snapping of fibers, the rustling of the crown of the tree: the pine tree seems to look around — frightened and wonder-struck. . . The crackling increases, a series of shots are heard, the tree sways, unsuccessfully trying to keep its balance, desperately shaking its bunches of needles. The edges of the sound are drawn apart, the wood-cutters remove the saw, jump aside. The tree still defends itself, still keeps its balance, like a rope-walker who has suddenly become dizzy under the top of a circus. Finally, at first slowly, then faster and faster the great mass of the pine tree falls to the ground, brushing against the adjacent trees, the twigs break and the tree lies motionless on the pressed down bushes. The battle is over . . ."

Shall Time's best jewel from Time's chest lie hid?
Or what strong hand can hold his swift foot back?

William Shakespeare, *Sonnet 65*

Chapter 2
Fracture – a Foe

CAN IT BE FORESEEN?

. ...**Yet this uncertainty was part of his exhilaration.**
Melvyn Bragg, *Without a City Wall*

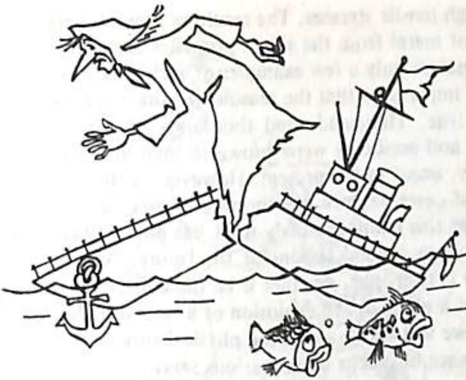
On the ninth of March 1934, a heavy beam designated for the thermodynamic laboratory of the Liège University spontaneously cracked along the entire 12 meters of its length.

On the second of December 1942, without the action of any external force, a crack 13 meters long originated in the sheathing of an all-welded tanker while still in the stocks. The tanker *Schenectady* of a displacement of 7 230 tons simply broke in half in calm water.

In 1973 a bridge across the Ohio river (USA) with a span of 336 meters fell down. This is what a witness relates: "For several minutes we anxiously watched the bridge oscillate like a ship rolling during a storm. Once it almost rose to the height of the pylons and then descended. Twisting along the entire span, half of the roadway almost turned upside down. Then, with an awful crash and din, the enormous structure came rushing down at a terrific speed from the dizzy height into the river."

More recently in 1976, before the eyes of many witnesses, in the center of Vienna a great column of dust appeared, the ground shook and the most important traffic artery of the capital of Austria, its link with the suburbs — the Reichsbrücke bridge — fell into the water. It was lucky that the catastrophe occurred early Sunday morning when there were hardly any cars and pedestrians on the bridge (in the peak hours, up to 18 thousand cars pass the bridge). Nevertheless some lives were lost. Broken pieces of the bridge blocked the Danube, which caused hundreds of cargo vessels and barges to converge together.

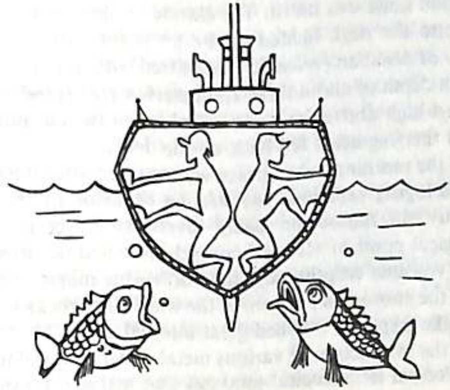
The extreme difficulty of foreseeing the results of sudden destruction can be seen from what once happened in a certain metallurgical works. In the steel smelting plant, the mixer, an enormous vessel containing several hundred tons of cast iron, burst. Unfortunately, the lower floor of the building was occupied by a laboratory which conducted spectrographic analysis for a whole



group of open-hearth plants. Due to the penetration of cast iron, the exit to the laboratory was shut off and it was set on fire.

A regrettable feature of catastrophes is precisely that it is difficult to predict their consequences: by the way, the word 'catastrophe' is derived from the Greek and literally means a sudden 'turn' or disaster that involves serious consequences.

It is hard to imagine all the kinds of catastrophes that can occur. Ships at sea, for example, run against cavitation. This phenomenon is associated with the appearance of discontinuity in the water in the form of bubbles. In the course of time they unite to form areas



with high tensile stresses. The resulting powerful elastic pulses tear pieces of metal from the ship's propeller and rapidly destroy it.

These are only a few examples of accidents. You may have gotten the impression that the reasons for them are inexplicable. This is not true. Thousands and thousands of various catastrophes, wrecks and accidents were known to man in the past and, unfortunately, occur in the present. However, in the overwhelming majority of cases, science has thoroughly analyzed their nature. It is true that this cannot remedy what has already taken place, but it can serve as a good lesson for the future. And, of course, each specific catastrophe, whether it be the collapsing of a bridge, the crash of a plane or the explosion of a reservoir, has its own roots. Below we will speak about the physical processes that lead to the appearance of cracks under various service conditions.

A STUMP ON THE ROADSIDE

This thought is as death, which cannot choose
But weep to have that which it fears to lose

William Shakespeare, *Sonnet 64*

The Soviet journal *Science and Life* writes: "On a dark Southern night, on the deck of the *Jean Charcot*, a French research ship making an exploratory trip in the region of the Azores,a sudden loud noise was heard. The alarmed sailors and scientists pouring onto the deck lighted up by projectors, discovered that the lumps of obsidian (volcanic glass) lifted with a drag the day before from a depth of about three kilometers, were exploding. The rocks jumped high above the deck, crumbled in the air and with a dull sound the fragments fell back on the deck.

In the morning, when peace was restored after the night alarm, the geologists explained the strange behavior of the rocks. Apparently, in the region being investigated, recently (from the geological point of view, of course) there had occurred an underwater volcanic eruption and the outflowing magma had solidified under the enormous pressure of the water. The rocks formed in this way, like a spring, retained great internal stress."

In the production of various metal structures, welding is one of the principal technological processes that makes it possible to obtain

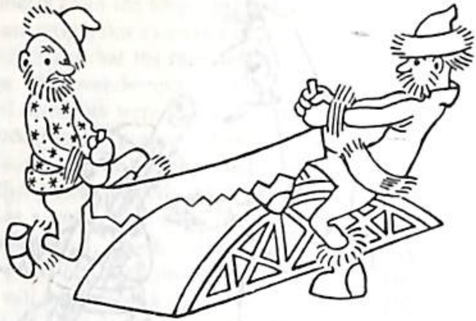
monolithic structures from the same or different metals and alloys and to produce articles that are spatially complex, which cannot be made otherwise. This valuable method has been proven in practice and has a big future. But it is not free from shortcomings. I want to speak about one of them.

The thing is that in welding, a considerable rise in temperature is confined to a small volume, while the rest of the metal remains cold. Such a difference in temperature often results in the appearance of great internal stresses within the structure. Sometimes they are so great that they themselves are capable of fracturing the structure. More often, although appreciable, they are still insufficient for producing spontaneous fracture. However, during use, the internal stresses are added to the external stresses and can cause a sudden catastrophe.

In one of his books, the Soviet satirist F. Krivin wrote that a stump stood at the very edge of the road and pedestrians often stumbled over it.

"Not all at once!", — squeaked the stump angrily. "I'll see as many people as I can: I can't tear myself into pieces, can I? What kind of people are you anyway, that you cannot take a step without me!"

The role of such a stump on the broad highway of welding and strength is played by internal stresses. Here are several examples



mentioned in a book by M. I. Gapchenko. Almost one fifth of 52 welded bridges built in Belgium in the years 1934-1938 were out of order by 1940 due to serious defects. Thus in March 1938 the bridge across the Albert Canal near Hasselt with a span of 73.5 m collapsed and in January 1940 — two bridges across the same canal, with a span of 61 and 48.8 m, broke down simultaneously. Between 1940 and 1950 in Belgium 14 cases of brittle failure of the elements of bridges were recorded. In Czechoslovakia in December 1951 a temporary railway bridge with a span of 12 m collapsed. One of the most outstanding accidents that occurred was the collapse of the Quebec (Canada) motor-road bridge that took place on the 31st of January 1951 at the time of a severe frost. The bridge fell down when only one car was passing over it. But that proved to be sufficient to cause all three spans, 54 meters each, to fall into the river.

Approximately 5 000 merchant ships were built in the United States of America during World War II. By April 1946 cracks were detected in more than one fifth of them. From November 1942 to December 1952, cracks were found in more than 200 ships. Ten tankers and three merchant ships of the *Liberty* type broke in half. In 25 other ships cracks completely destroyed the deck or bottom. In March 1943, the tanker *Esso Manhattan* of a displacement of 10 344 tons broke, although there was only slight rippling at the time. The stresses in its body were insignificant. The tanker *Sackets Harbor* was cut by a crack immediately after it was built, while still in the dockyard.

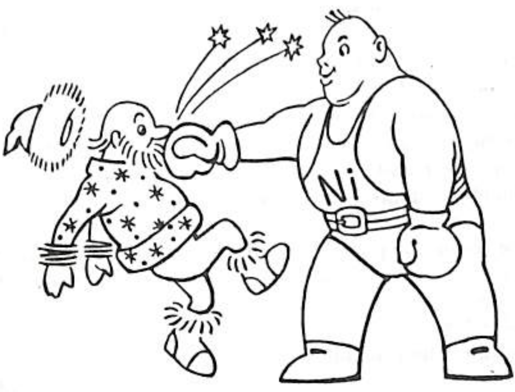
The examples cited above should be enough to understand how dangerous internal stresses and the cracks 'provoked' by them are.

Their number is sufficiently great, and the costs incurred by the accidents described amount to millions of rubles.

Let us try to explain what the enormous force of thermal stresses stems from.

In the first place this should not arouse any wonder. There is no reader who does not know that a thick-walled glass will break if we fill it quickly with boiling water. It is obvious that the instantaneously expanding inner layer of the glass comes into conflict with the cold outer layers that have not had time to warm up. The latter will be under tension and if the heat inside the glass is not absorbed by a metal spoon immersed in the boiling water, the glass will break. The crack that appears on the surface will encircle it, moving at first along the generatrix, then along the bottom, and finally completing fracture along a second generatrix. Sometimes thin-walled glasses crack from boiling water when they are placed in a glass-holder that embraces the glass too tightly: the glass-holder does not allow the glass to expand and the thinner the wall of the glass, the more easily it breaks. The glass can break a long time after hot tea has been poured into it. This happens if the glass has a conical shape or it fits too tightly in the glass-holder as the result, for instance, of vibrations of a railway car in motion. When the tea cools down, the metal glass-holder, which contracts faster than the glass does, crushes the glass.

The phenomenon described above is called by physicists internal stress of the first order. They say that this stress is counterbalanced



in the entire volume of the article and produces deformation and fracture in it as a whole.

Such internal stresses of thermal origin we encounter often and quite unexpectedly. In the winter at the time of severe frosts, booming sounds resembling shots can be heard in the forest. They are usually caused by the rapid breaking of oak trees; frost fissures, i.e., cracks appear in the bark. Acoustically this is manifested by the sound of a rather loud 'shot' similar to what we hear in the case when almost any brittle structure breaks.

That is quite natural, since the reason for this is thermal stresses caused by a drop in temperature which is low at the surface of the tree and higher at its core. The fracture of tree trunks due to frost is quite usual and many species of trees suffer from this phenomenon.

The Soviet poet S. Ostrovoy has observed an interesting phenomenon — another way tree trunks are injured as a result of thermal stresses:

So terrific was the cold
That successively each knot
Popped out with a sound as loud
As the crackle of cannon shot.

Let us recall the glass and the metal glass-holder; the knot can play the role of the former and the core of the trunk, that of the latter.

Characteristic of both these cases is the appearance of thermal stresses immediately after the change in temperature takes place. However, in the first place, internal stresses may not be associated with temperature, and in the second place, regardless of what caused them they can be retained in structures and parts for an unlimited time. In this case they are called residual or internal stresses. A simple example is the stress intentionally created in a piano, violin, cello or guitar when they are tuned, i.e., when their strings are tightened. The strings are stretched and the frame of the instrument is compressed. Evidence of this is the rupture of strings when the performance of the player is exceptionally temperamental. The frames of pianos have been known to break due to compression caused by the tension of many strings with a force of several tons.

Such stresses, however, are distinguished by their usual state of equilibrium. The residual stresses deforming parts of the structure under elastic stress are compensated for by the strength of the in-

strument. As a result, the whole system consisting of two opposing forces — the internal residual stresses and the resistance of the instrument — is, so to speak, paralyzed in a temporary state of balance. There are several ways out of this condition. The simplest one is the 'peaceful' gradual decrease of tension due to an increase in temperature or aging — it is called relaxation. In stringed instruments it is manifested in the undesirable but continual elongation of the strings (it is said the instrument gets out of tune). There is another possibility, that results in a catastrophe, in which either because of a decrease in the strength of the structure with time, or due to the action of an external force, or for both reasons, the system under tension simultaneously loses its equilibrium and breaks, releasing the accumulated elastic energy. That is what it is like in the case of glass 'tears' (Prince Rupert's drops). Imagine that drops of liquid glass fall into a vessel with water. While falling they acquire a pear-like shape with a thin curved tail like that of a toad. This glass 'comma' quickly hardens from the outside, while it remains liquid inside. As a result, great internal stresses are produced — in the middle of the 'tear', compressive stresses; in the outer layers, tensile stresses. The remarkable strength of glass 'tears', their ability to withstand the blows of a hammer on their thicker end, is due to the compressive stresses that prevent the formation of microcracks. But it should be remembered that the source of this great strength is the internal stresses that are balanced and 'shut up' in the entire volume of the 'comma'. And to destroy this strength it is enough to break off a tiny piece of the toad's tail. The powerful compressive stresses that are no longer restrained by the strong band of the expanded surface layer, break the glass, converting the beautiful clear glass 'tear' into a cloud of scattered minute glass grains.

Such processes are also not rare in metal structures. Thus, in February 1943, near the city of New York, a spherical welded reservoir for storing hydrogen broke. Its diameter exceeded 11 m and it had a wall 16 mm thick. The gas holder which was designed for a working pressure of 5 MPa failed to withstand . . . 0.35 MPa. Prior to the accident the temperature of the surrounding air dropped to $-12°C$ while from one side the vessel was heated by the sun. This was sufficient to cause fracture accompanied by an explosion, breaking the shell into 20 pieces. In the United States, during 35 years (from 1918 to 1953) 32 reservoirs broke, incurring a loss of half a million dollars.

Most often the accident took place mainly because of the low quality of welding and the high thermal stresses in the structures. Cracks originated either in the parent metal in the vicinity of many weld seams or in edge welds with poor penetration. In the majority of cases, as a result of the accident, the metal flew to a considerable distance, sometimes up to 40 m. It is fair to point out that besides internal stresses, other factors also acted here: first of all the poor quality of the parent metal and defects in the weld seam which played the part of incipient cracks. Of no little importance was the embrittlement of the metal due to lowering of the surrounding temperature. About this phenomenon we will speak in the next section.

COLD AND FROST

Nature always has a trump card in reserve.

Arthur Clarke, *Rendezvous with a Medusa*

Vast territories formerly completely deserted and uninhabited are now being populated: the extreme North and Siberia in the Soviet Union, Alaska in the United States, the northern regions of Canada, Greenland, Antarctica . . . The conquerors of these regions encounter many obstacles. One of them directly applies to materials. This is what would take place if the principal structural material used in machine building — steel — were 'taken ill'.

A gigantic train composed of hundreds of cars, travelling at a speed of 70-100 km/h fell down a slope. The reason for this is very simple — the rails cracked. A huge bridge truss spanning across a wide river suddenly fell down together with the electric locomotive on it. Heavy trucks stop due to the mass breaking of parts. In factories and plants ceilings made of reinforced concrete hundreds of meters long fall down seemingly without the action of any external force. Gantry cranes and dump trucks, oil and gas pipelines, drags for obtaining gold and diamonds break like matches.

Perhaps the author with a view to dramatizing has intentionally exaggerated or simply made up these events? As a matter of fact, he has not — he has even understated them, failing to reveal all.

Judge for yourself. The trigger that initiates the fracture of steel is a drop in the temperature. In this respect most steels are like


Mo
Ni
Ti
Zr
Mo–Ni–Ti–Zr

sickly people — at the slightest overcooling they take ill. In some steels, for example low-carbon steels, 'pneumonia', i.e., fracture, begins at $-60°C$ to $-70°C$; and in high-carbon steels, already at room temperatures. Cast iron is very brittle under any conditions. Moreover, the climate in some of the regions of this country is very severe. Temperatures below zero persist over 8 months of the year in Norilsk, Yakutsk and Magadan. The lowest temperature recorded in Norilsk was $-57°C$; in the Magadan region, $-65°C$; in Uste-Nere (Yakutia), $-72°C$. In the northeast and northern regions the average temperature during a year is within the limits of $-4°C$ to $-17°C$ and in December and January from $-20°C$ to $-50°C$. In such conditions, metal that is not protected against frosts and violent windstorms is subjected to great dangers.

To be fair it should be pointed out that cold brittleness is not always the result of natural conditions. More often it results from technological processes that require low temperatures, such as those occurring in plants to obtain liquid air ($-180°C$), liquid oxygen ($-183°C$), liquid helium ($-273°C$), liquid hydrogen ($-253°C$), liquid nitrogen ($-195.7°C$) and also in various refrigerating plants. We have to deal with extremely low helium temperatures and special properties of metals when obtaining superpowerful magnetic fields with the aid of superconductors. And, finally, all space flights take place at temperatures close to absolute zero.

We pay an incredibly high price for cold brittleness; because of it equipment in Siberia and the North is sometimes idle for months. Finally, fracture is always dangerous.

What causes the embrittlement of metals at low temperatures — this astonishing and treacherous phenomenon?

There are two answers. A convincing one — that of the metallurgists and metal experts, and the unconvincing one — that of physicists.

It is well known that metals with body-centered cubic lattices are susceptible to cold brittleness, whereas most steels with face-centered lattices, i.e., austenites, do not fear a drop in the temperature. And metals in general (not only steels) with face-centered lattices, almost never break because of the cold — for example, copper and aluminium. However, the great majority of metal structures are manufactured from ordinary steels with body-centered lattices because these steels are relatively cheap and therefore such structures are unprotected against 'colds'.

These steels are subdivided into two groups: rimmed and killed steels. In the process of steel making there arises the question: what should be done with the oxygen that is dissolved in it? Should it be removed under compulsion or should it be given a chance to escape by itself? The former is attained by the technological operation called deoxidation. It consists in introducing into the ladle with liquid metal manganese, silicon and aluminium, that combine with the oxygen to form compounds that are insoluble in the metal. During subsequent solidification of the steel it is calm; it does not bubble because gases are no longer evolving from it. As concerns rimmed steel, it is not completely deoxidized before casting, and during solidification in the casting mold it 'boils', i.e., evolves bubbles of carbon monoxide. The escape of gases is intentionally prevented and carbon monoxide in the form of scattered gas bubbles and blisters is entrapped in the metal. During rolling, these defects are welded in it. As shown in practice, however, rimmed steel is more subject to embrittlement, and machine parts made from it, though cheaper, are more readily broken in the winter.

Metallurgists also give definite answers to the question of what effect the composition of steel has on its behavior during frosts. Carbon causes embrittlement; manganese, on the other hand, increases cold resistance. Silicon also has a favorable effect. Nitrogen, sulphur, phosphorus, hydrogen and oxygen are obviously harmful, reducing the resistance of steel against brittle failure.

Alloying elements that provide steel with a reliable shield against the sword of cold brittleness have long been known. These are primarily nickel, molybdenum, zirconium, and titanium. Small additions of vanadium, chromium, copper and aluminium can be useful too. There are also so-called modifiers that are added in small quantities to steel. They include, in the first place, the rare-earth elements.

Thus, from the point of view of the metallurgist, the problem of cold brittleness is solved and amounts to the following. If the temperature of the surrounding atmosphere is not lower than +20°C, in the case of impact loads use can be made of rimmed carbon steels. In the case of static loads, these steels can work at temperatures from −20°C to −30°C. Semi-killed and killed carbon steels can stand temperatures from −30°C to −50°C. But for more severe frosts, alloying is indispensable. Steel containing 3.5% Ni works well from −70°C to −120°C; and carbon steel containing 8.5-9% Ni, even down to −200°C. As concerns lower

temperatures, they require austenitic steels capable of withstanding 'frosts' down to $-253°C$ without breaking. To sum up briefly, what is needed for the operation of metal structures in climatic regions with a low temperature is high-alloy steels suitable for performance in the North. And although they are very expensive, a cross-country vehicle for antarctic conditions made of alloyed steel and submitted to heat treatment is guaranteed against sudden breakage in any frost.

But is this sufficient? Can it be considered that the past thousand years of experience involving irreparable mistakes and irredeemable losses have taught man to cope with such destruction? Apparently, only partially as yet. More exact knowledge is needed.

Deep comprehension of the nature of cold brittleness is, unfortunately, still far off. And what physicists have to say about cold brittleness, I would say, amounts to opinions fraught with doubts.

Here, for example, is one of the points of view. There are two ways that metal can break; by brittle or by ductile failure. In brittle failure the interatomic bonds are directly ruptured. In ductile failure, plastic flow precedes rupture. Practical experience seems to confirm this. When we break glass by striking it with a hammer or when slate breaks and crumbles in our hands, our eye does not notice any deformation — we only see that the object is broken. But let us try to rupture a piece of polyvinyl chloride insulation tape or a piece of copper or aluminium wire. We see and feel considerable deformation before fracture itself sets in. This deformation plays the role of a buffer that dampens the external force, consuming its energy even prior to the breaking of interatomic bonds.

Some physicists believe that this plastic deformation constitutes the key to understanding cold brittleness. Unlike the strength of interatomic bonds, which does not change within the interval of $+50°C$ to $-50°C$, plastic deformation in metals inclined to cold brittleness is very sensitive to temperature. Consequently, with a reduction in the temperature the deformation grows weaker which reduces its buffer action. As a result, the external force is transferred directly to the mouth of the crack where it is spent on the rupture of interatomic bonds.

Actually, however, everything is much more complicated than this. Fracture resembles the two-faced Janus. It not only consumes the energy of the external force, but it generates microcracks which are capable of growing even during deformation.

According to other points of view the brittleness of steel at low temperatures is due to changes in the strength of interatomic bonds, the level of which drops. Some authors attribute cold brittleness to specific processes in which the spin (the rotation of an electron about its own axis) occurs mainly in definite directions. Some scientists believe that cold brittleness signifies the appearance of new polymorphic transformation, i.e., the transition of the crystal lattice from one form to another . . . These, however, are all only hypotheses. The future will tell whether they are correct or not.

UNPLEASANT CONSEQUENCES

Ominously things in the house begin to break,
as if they were shoved by some invisible capricious destroyer . . .

(After P. Neruda)

In a Soviet journal G. Podkupnyak writes: "The commander ordered the men to stop firing at once and abruptly bent over the mounted gun. Even with the naked eye the artilleryman noticed a winding crack on the barrel of the gun . . . All five guns displayed barrel damage after the first shots." The reason for this, most probably, was the faulty heat treatment of the barrels.

We have already spoken of the harmful effect of residual stresses. However, they do not act openly and straightforwardly but in many veiled ways: for example, one or a few cracks may appear that weaken the given structure and are capable of growing under the influence of the very same residual stresses. We rather often encounter cases where residual stresses act as an intermediary in fracture.

In this connection let us turn our attention to the heat treatment of steel — a technological process employed in producing any of the critical parts of machines and mechanisms.

Most kinds of such treatment involve the structural transformation of austenite to martensite. Austenite consists of a close-packed system of atoms arranged in the form of a cube where the ferric atoms are situated at the vertexes and in the center of its sides. In contrast to this, in harder and more brittle martensite, the atoms which occupy the vertexes and the center of the cube are less com-

pact. As a result, the volume per unit of mass in austenite is less than that in martensite. This fact explains why great stresses arise on cooling steel rapidly from high temperatures (at which it is in the form of austenite) to low temperatures (where it is converted to martensite with sufficiently fast cooling). The transformation of austenite to martensite does not proceed uniformly and simultaneously throughout the cross section of the part. The process schematically consists in the following. The outside layers of the part acquire the structure of martensite sooner than the inner layers, and the metal for some time becomes two-layered: martensite on the outside and austenite on the inside. Later, as the inner layers are cooled, the austenite in them is converted to martensite and the volume of the interior of the part will begin to grow; but the outer layers of martensite will oppose this. As a consequence, the outer layers will be under tension while the inner layers will be under compression. This is what internal stresses are composed of. Thus, after heat treatment we obtain very hard metal; but it is difficult to make use of it because of the great stress and, consequently, the liability to breakage at any moment.

Similar processes, but on another scale, may occur when chemical elements are distributed unevenly in the cross section of an object — for instance, in chemical treatment at elevated temperatures, consisting of impregnating the surface of the metal with some element or other. In this case, at high temperatures, austenite of another chemical composition is formed that is converted to martensite in a different way and at different rates.

These phenomena are superimposed by internal stresses of thermal origin, that are produced by cooling or heating a part, due to

dissimilar expansion and contraction of the various structural constituents.

In one way or another the heat treatment of steel generates rather great stresses, frequently of a steric nature, which lead to the appearance of various cracks in the metal. Sometimes they are single deep cracks in objects of complex configuration, for example, in milling cutters; other times internal bow-shaped cracks found, for instance, in carbonized steels (steels whose surface is saturated with carbon). Other kinds of fracture are also encountered — in the form of many cracks that cover the entire surface of the part, for example.

Where is the good, if a critical part contains a hundred cracks? As a matter of fact we know that even one may be enough, because it is impossible to foretell how such a part will behave under stress. Since it is more farsighted to anticipate the worst, fracture can be expected from a single crack that happens to be in a more 'favorable' position. It is like in that sad joke about the victim who received four wounds, two of which were fatal and two others, fortunately, were not. In short, cracks that originate during heat treatment are harmful and dangerous.

But besides that, there are several secondary reasons why heat treatment causes anxiety. For instance, the magnitude of the stresses leading to breakage (produced by external or internal forces) diminishes with time. As a result, if the duration of stress is prolonged, the strength of the steel is reduced several times. In some steels, in particular, in high-speed steel, surface cracks are 'provoked' by the decarbonized layer, i.e., the surface metal film which for some reason or other has been left without carbon. Steels that undergo heat treatment are very sensitive to any stress concentrators (various cuts) on the surface and within the material. Such a concentrator produces its own field of elastic forces that are added to the residual stresses and cause premature breakage. Not the least role is played by the various excess phases in steel, especially those located at the boundaries of the grains. They often play a decisive part in generating cracks after hardening. In short, there are many serious causes, and there are some that are not so serious, yet they lead to serious consequences.

Heat treatment, in particular the hardening of steel, increases mechanical strength and therefore is essential for machine building. Nevertheless, it introduces cracks in the metal that are fatal for the structure. Fortunately, there are many ways of eliminating the ap-

pearance of cracks, thus preserving the advantages afforded by heat treatment. These methods are not always simple, but . . .

One rigorous law is in force
For man and metal alike
Without a struggle, of course,
Steel does not become steel.

(After Ya. Belinsky)

You probably remember that in the heat treatment of steel, the internal stresses are 'the fly in the ointment'. It is namely they that cause the appearance of cracks. Consequently, it is of the foremost importance to extinguish the tension in the part.

This can be done in several ways. Here is one of them. Besides structural stresses there are thermal stresses which arise at elevated temperatures when the metal is still very plastic and phase transformations have not set in yet. Apparently, if the rate of cooling is high enough these stresses can cause plastic deformation of the part and be discharged, i.e., no longer be dangerous.

In the case of structural residual stresses, the contrary is true — rapid cooling at low enough temperatures merely gives rise to many cracks. Therefore it is expedient, at temperatures lower than that at which austenite begins to decompose into martensite, to conduct cooling gently and very slowly. Such gentle treatment of steel is often achieved by quenching in oil, since it cools at a slower rate in oil than in water. It is obvious that in all cases, internal stresses will be determined by the initial temperature at which hardening is begun. That is why it is recommended that as low a temperature as possible be chosen.

A reliable method of removing internal stresses is by tempering, i.e., repeated heating after hardening, during which the metal and its structural constituents adapt themselves to each other. It is something like the jostling of passengers in an overcrowded trolleybus: everybody somehow finds a place for himself; all get accustomed to each other and continue to ride on as if 'the more the merrier'.

In the language of heat treatment this means that the thermal 'jostling' of the structural constituents removes the internal stresses.

Alexander Green once said that reality, for the most part, ties and unties knots at a slow rate. Hardening is different — in the matter of a few seconds, phase transformation takes place, and

powerful residual stresses and cracks are produced that are followed by inevitable breakage. Therefore, it is important not to delay tempering, keeping in mind that in the course of time the strength of a part under stress decreases. That is why tempering is conducted immediately after hardening.

FATIGUE IN METAL

> **Be it a castle or hostel, alike**
> **All will most surely be crushed by time's heel;**
> **Nothing can withstand the weight of years,**
> **Neither buildings, nor iron, nor granite.**
>
> (After S. Petöfi)

We are not surprised when a person grows tired. The strength of metal is also limited. But whereas a person tires doing any work, the metal 'tires' only as a reaction to a definite kind of loading — the repeated application of a load of the same or opposite sign. How is fatigue manifested in inanimate materials? First it undergoes plastic deformation, then it breaks. But that is just what happens under ordinary loading, isn't it?

It may seem that in both cases everything is just about the same — the same deformation, microcracks, failure. However, fatigue substantially differs from fracture caused by a load that is applied only once. Let us try, at least superficially, to understand the difference.

First of all, metals in the world surrounding us are constantly subjected to the action of pulsating loads. The iron carcass of a building continuously receives microscopic vibrations from the ground because in it feeble elastic waves caused by underground volcanic forces on our planet never stop flowing. The frame of an industrial plant with metal-working machine tools also continuously vibrates. The framework of a lathe vibrates because of the contact of the cutter and the object it cuts. So do the engines and frames of airplanes and automotive vehicles. It is obvious that these vibrations affect the state of the metal. But just how? Sometimes tragically — a plane falls to pieces in the air. Rails that are repeatedly bent under the weight of trains split. Shafts bearing

heavy flywheels and wheels under the action of loads and unbalanced centrifugal forces bend alternately in different directions and break. And what a dreadful sight is that of a wheel torn away from a heavy truck, jumping up and down on a road. So we see that metal fatigue is sometimes manifested quite dramatically.

What are the specific features of fatigue from the point of view of mechanics? First of all fatigue fracture involves plastic deformation, but to a much lesser degree than in the case of one-time failure. An especially dangerous feature of fatigue fracture is its ability to begin and proceed at stresses considerably lower than the ultimate strength or yield point. In fact they do not exceed elastic stresses, but repeated loading employs them so effectively that it succeeds in breaking the material. If the stresses are considerable, fatigue fracture sets in earlier. But if the stresses are very small that only means that the number of cycles has to be greater. At its disposal metal has a certain service life (endurance). It can withstand a definite number of loading cycles, which falls as the stress increases. This is quite natural. A person also gets tired depending on the work he performs. The harder it is, the sooner he gets tired. But, of course, the magnitudes of metal fatigue are different. When a reasonable external load is applied, steel is capable of withstanding tens of millions of loadings. Take, for example, the springs of an automobile. What a great number of vibrations it has to withstand from every small stone and uneven surface, in order to assure safety and comfort in motion. And what about all the different valves in an engine, working continually and at high temperatures too? Thus, the process of fatigue proceeds because small stresses are enhanced by the repeated application of the load. This leads to fatigue and aging of the metal. It would be wrong to think that only certain weak metals 'tire'. On the contrary, this is a general phenomenon to which any metal is subject, be it even extra-strong steel!

If the mechanical, i.e., the exterior features of fatigue are clear enough, the physical mechanism of the process is much more complicated. Let us begin with plastic deformation. As distinguished from one-time loading, plastic flow in fatigue is concentrated in a smaller area. In both cases plastic deformation proceeds as a dislocation mechanism. However, instead of the appearance of an ever growing number of slip lines, as in ordinary deformation, fatigue is accompanied by the formation of a limited number of slip lines and their subsequent expansion. A fundamental law of fatigue

is that all the processes lack uniformity throughout the cross section of the metal. Fatigue is a process that is capable of selecting the weakest links in strength and of concentrating its undermining force on them. The properties of the main mass of the metal may be untouched by destruction. We will give some examples of how treacherous selectivity of fatigue failure can be.

First of all, it appears that concentration of stress in fatigue causes embrittlement of metal much sooner than under conditions of ordinary loading. In repeated loading, metal becomes more sensitive to diverse concentrators such as surface defects, cuts of all kinds and corrosion.

Non-metal inclusions, in particular, are always stress concentrators. But in the case of fatigue they become really dangerous because repeated loading immediately concentrates plastic deformation around the inclusions, and, already in the early stages of fracture, when the main mass of the metal is still sound, generates microcracks in them. This is promoted by the fact that the inclusions which after smelting were firmly 'glued' in the metal matrix, with time tear away from it and are no longer bound to the metal; stress concentration increases at once and, consequently, the probability of slips and microcracks in the vicinity of the inclusions abruptly increases.

As a result of non-uniform deformation in the cross section of the 'tiring' metal, the total amount of energy spent on plastic deformation in repeated loading of metal is less than in the case of ordinary deformation. Thus non-uniform and selective fracture 'save' the metal as a whole from deformation and fracture. However, one or two weak spots are bound to be found — which is just right for fatigue to proceed. In this way the metal may fail due to fracture concentrated in a very few places that are vulnerable to the generation of fatigue cracks. As far as the general great strength reserves of the metal are concerned, they remain unused. This creates the danger of fatigue which finds the weak spots in the metal and makes the most of them.

Selectivity, which makes fatigue possible, is the main problem involved in securing strength in metal. The metal should have equal strength throughout its entire structure. But this is impossible in a real metal which is non-uniform from its birth — because it is a polycrystal, because it is an alloy and because various impurities and defects are scattered in it. Consequently, it has many weak spots which are unerringly found by fatigue. But only one is sufficient for fracture!

What is the physical mechanism of the generation of microscopic cracks in repeated loading like? First of all, it may be almost any of the dislocation mechanisms described in the first chapter. But there are also specific fatigue models. One of them is the schematic pattern proposed by the Japanese physicist Fudzita. When in one slip plane unlike edge dislocations draw together, in one of them the extra plane is on top, while in the other it is at the bottom. Naturally, they unite and the dislocations vanish, are annihilated. Now imagine the same dislocations but in different, though close, slip planes. At the base of each extra plane there is an empty space not much larger than that between atoms in a sound crystal lattice. These voids in the two unlike dislocations unite to form an incipient microcrack. Other pairs of dislocations in the vicinity likewise undergo such a process of uniting. As a result of many such acts the incipient microcrack grows and becomes stable. Subsequently, it increases because of the influx into it of dislocations from the slip band. And, finally, it becomes a crack. Fudzita in his dislocation model very cleverly made use of the fact that fatigue is sensitive to various inclusions and segregations. He assumed that due to the frequent movement of the dislocations back and forth in the slip band (loading is repeated), oxidation takes place in the vicinity of the slip lines. The reader may ask where the oxygen in the middle of the metal comes from. The question can be answered in two ways. In the first place, oxygen and other gases remain in the metal during smelting. In the second place, the slip lines emerge on the surface of the metal where there is an unlimited amount of oxygen. And if this question is dismissed, then Fudzita's hypothesis signifies the following. Oxides are formed in the slip bands. Particles of oxides are barriers for dislocations. And from here, as we know, there is only one step to a crack.

There are many ways that dislocations interact to produce point defects (vacancies). There is no doubt that in the process of fatigue a great number of them are formed in the metal. This gives rise to various hypotheses concerning the accumulation of vacancies to form pores or lacunae. Such cavities can become sources of fracture. The simplest variant of the conversion of a cavity into a crack is its 'flattening' under the effect of external loading.

The Soviet scientists I. A. Oding and V. S. Ivanova believe that the origination of fracture is connected with the enormous energy of elastic deformation that arises in certain microvolumes. Then initial fracture can flare up, for instance, due to the ordinary process of smelting.

Certain phenomena take place in fatigue that are not encountered in the case of ordinary fracture. Thus, in repeatedly loaded metal, thin flakes of the material are forced out of the slip plane. This is called extrusion. Intrusion, the opposite process, in which metal is drawn in, is also known to happen. Just how these processes arise is still controversial. Nevertheless, some scientists believe that the origination of cracks may be associated with them.

On summing up our ideas on the nature of fatigue, we find that there are not many of them. But that should not frighten us. Only a wise man is capable of saying, "I do not know this." . . . For only a wise man knows the real limits of his knowledge.

This *not* has its charm for so much that is very interesting is still unknown. Of course, there are no limits to knowledge. And those who today are taking entrance exams in some higher institute of education will, in their time, extend the limits of knowledge and solve new problems!

It should not be forgotten that the problem of fatigue is of the greatest importance in modern engineering. There is no branch of industry where it does not figure as a naked evil that injures different kinds of axles, gigantic rotors, the crankshafts of engines, the blades of steam, water and gas turbines. And what about aviation? Ever since the series of accidents occurred on the British *Comet* passenger planes, such rapid fatigue has been something everyone is talking about. No wonder. All planes on reaching high altitudes are 'inflated' because the internal atmospheric pressure remains almost unchanged while the external pressure falls. On landing, the pressure is equalized. During the service life of a plane, several hundreds of such cycles occur. And as in the body of a liner there are port-holes, hatchways, thousands of rivets and other stress concentrators, a crack may be generated, which in these conditions constitutes a direct threat to the lives of hundreds of passengers.

And what is fatigue in deep-water submarines? When the body of the ship is submerged it undergoes incredible compression. On rising to the surface, not only the people in it, but the ship itself sighs with relief and expands. This process after being repeated many times must also give rise to fatigue in the metal.

The last two examples emphasize the importance and urgency of thoroughly understanding everything that is connected with fatigue. And as this concerns the most responsible branches of industry, all available means, all effort and talent of scientists all over the world, will without doubt be concentrated on the study of the

problem of fatigue. This will certainly lead to the solution of the whole problem. It is hard to say when this will happen. But, probably, in upcoming decades.

AN EAGLE'S EYE IS NEEDED

—You were trying to do — what?
— I was searching for a flaw, my friend.

Agatha Christie, *Murder in the Orient Express*

The well-known Soviet writer A. I. Kuprin relates an old tale about how the empress Savskaya, desiring to test the wisdom of King Solomon, set him a riddle. " . . . she sent Solomon a diamond the size of a forest nut. In the diamond there was a narrow, winding crack. The task was to draw a silk thread through it. The wise king let a silk worm into the opening of the crack, which making its way out of the diamond left a thin silk web in its wake."

To be sure, at the present time, the problem could be solved by an ordinary man. First of all, the crack that Solomon had to do with was a relatively wide one of the order of a millimeter in cross section. In the second place, it emerged on the surface and could be seen with the naked eye. In the third place, the crack appeared in a transparent diamond. In short, the king knew everything about it. This, of course, does not belittle his wit in threading such a 'needle's eye' with the aid of a worm. But. . . the real problems that confront specialists concerned with the strength and fracture of metals are much more complex.

Let us begin with the fact that cracks are not always large in size. If they were too large, the object would no longer exist as a single whole. Quite often cracks are actually of microscopic dimensions, i.e., they can be seen only under a microscope. And not just any microscope will do. Sometimes not an optical, but an electron microscope is needed. That means that such microcracks are thousandths and even millionths of a centimeter long. Moreover, neither is it possible to find a worm that could be let into a crack with a cross section of only a few interatomic distances. But even if by chance we did find a living thing that could be squeezed into a flaw, it would find itself in a 'blind alley' (cracks are not endless in

length) or in a hopelessly intricate labyrinth. And far from all cracks come out on the surface.

In reality metals constitute a world permeated with a fantastic number of microcracks. I'm referring to sound metal that has been properly smelted, rolled and heat-treated, observing all rules and precautions. In some ways it reminds one of an old cracked ceiling. The cracks form extremely complicated patterns; look at them intently and if you use your imagination you can see a railroad junction branching out web-like; fantastic beasts; amazing faces. Shouldn't we be concerned about the strength of the metal?

But we already know that for some time there is nothing to fear because the cracks are subcritical. Just the same they must be kept under control. How can this be done? In transparent materials the smallest cracks that are visible under a microscope are of the order of a few thousandths of a millimeter. But what if they are still smaller? Then use can be made of the dispersion of light caused by microcracks. Imagine that you are at a hockey match. Five minutes before the match starts the stadium is very lively; all the lighting fixtures are switched on, but for some reason it is still quite dark. The fact is that the light beams enter the highly polished layer of ice at an angle and are reflected in it from one surface to another. A great deal of light is actually entrapped in the layer of ice and 'leaves the game', i.e., is lost as far as lighting goes. But 5-10 minutes have passed, and though the current in the lamps has not changed and no new projectors have been switched on, the light is distinctly brighter. What has happened? The skates of the hockey players have cut the surface of the ice. The resulting grooves and numerous cracks that penetrate into the ice do not allow the light to pass into the layer of ice, dispersing it into the surrounding space. This is also how the microscopic cracks in a transparent crystal disperse light. Owing to this it is possible to examine the cracks of a size close to the length of light waves (about 5 ten-millionth parts of a meter). Perhaps, by scattering light, it is even possible to study the birth of the very first minute cracks one interatomic distance long? No, that is impossible. That would mean repeating the mistake made by the very fine Soviet poetess Marina Tsvetaeva who wrote:

Like Hamlet, Prince of Denmark, surrounded
By a nimbus of awareness and lost faith
Deadly pale — to the very last atom . . .

Can an atom of our body have color or be pale? No, for two reasons. First of all, because we see light reflected and scattered by us and not that emitted by the body. And second of all, an atom is 5 000 times smaller than the length of a light wave. If a travelling light wave encountered a solitary atom or . . . a microcrack of the same size, it would simply go around it. In other words, it would, in fact, not notice it, just as a big wave takes no notice of a thin twig stuck in the bottom of the sea.

But what should we do to be able to see incipient cracks, much more, those in opaque materials? In this case use should also be made of dispersion — but dispersion of electromagnetic waves of a size close to that of interatomic distances. "Of X-rays", the reader will make a shrewd guess, and he will be right. It is precisely the dispersion of X-rays that makes it possible to study the distribution of the smallest atom-size cracks in metals and monocrystals.

However, the dispersion of electrons is a serious rival to the dispersion of X-rays. In recent years electron microscopes have been perfected to such a degree that they are actually capable of observing the behavior of a single atom. No wonder this method is so promising for observing the very first stages of the appearance of microcracks. And if for our predecessors the highest attainable skill was, figuratively speaking, 'to shoe a flea', in the near future it may become necessary to 'shoe' an atom, say, to restore its cohesion to its neighbor. Then electron microscopy will be the most effective, and what is of the greatest importance, the most visual method available.

And what about practical problems such as when at a plant there is a steady flow of heat-treated parts that must be free of large and obviously dangerous cracks? Here the problem is simpler because the length of the cracks is equal to fractions of a millimeter and more. The number of methods for determining the size, location and direction of a crack is the greater, the greater the size of the crack. Let us suppose that at the beginning the crack is quite small. In this case the fluorescent method can be used. The metal on the surface of which cracks may appear is wetted with a special solution that possesses two valuable properties. First of all, it is capable of penetrating into the smallest cavities and filling them up. In this capacity of a pioneer it makes sure that, if there is a crack, the liquid (kerosene, for example) will make its way into it. The second property of the solution is its ability to glow under the effect

of ultraviolet light. The part was first wetted by the solution which, after some time passed, was washed off the surface of the metal by a stream of water. Then the metal was illuminated by ultraviolet rays, after which:

The surface of the smooth metal
Was more colorless than glass.

(After Ch. Baudelaire)

Because there was no longer any kerosene on it. The presence of a crack is revealed by the luminescence of the kerosene which has penetrated into it and been retained there. The light emitted is very faint because there is very little liquid in the narrow crack and the luminophore remains only at the bottom of the crack like at the bottom of a deep and narrow canyon. Light does not emanate in all directions but only in those determined by the faces of the crack. That is why the metal is examined in the dark. The ultraviolet rays are invisible but the faint luminescence of the luminophore in the crack is noticeable.

Industrial plants widely use the magnetic method, which is based on a simple principle. Suppose that in some way we create a magnetic field in the metal. It will tend to spread out uniformly throughout the cross section of the metal. But if there is a crack in it there can be no uniformity; the magnetic field will concentrate at the tip of the crack. And if the crack is a closed one, magnetic poles

are formed on its edges at the apex. Now let us pour finely powdered iron into a liter of kerosene, stir the mixture, and pour it onto the part. The grains of iron, being capable of moving easily in the liquid, will settle on the part, concentrating mainly at the magnetic poles. Thus, the crack will be 'exposed'.

The absolute though uncrowned king of flaw detection, however, is ultrasonics. The reason for this is that this method detects cracks of diverse sizes — from fractions of a centimeter to many kilometers long. With time the lower limit will be about 100 times less. Ultrasounds are 'omniverous' — they will find any crack, those that come out at the surface and those concealed inside the metal. It does not matter whether the crack is wide open or whether its faces are only slightly parted. The equipment needed in this method is portable. No wonder it is used all over the world. It can be employed to detect flaws in any branch of industry; at a plant and in the field, in the endless lines of oil pipes.

What is the method based on? Primarily on the fact that ultrasound cannot pass through air or a vacuum. It likes 'solid ground' and can propagate only along the metal. Therefore, should there be a crack in the path of an ultrasonic beam, it cannot go ahead. It is quite easy to check this. But, besides being afraid of cracks, it literally recoils from them — is reflected like a sunbeam from a mirror and moves backwards. It is easy to catch it and if we take note of its path we will receive the beam's answer to the question: what has happened? As is well known, the angle of incidence is equal to the angle of reflection.

And if this is so we can always ascertain the angle at which the crack is inclined.

Not so long ago in Alaska, at the cost of 7 billion dollars, an oil pipeline about 1 500 km long was constructed that could convey 60 million tons of oil a year. The pipes in such a type of oil pipeline are connected by welding. The quality of the welds was checked by the most widely used and reliable method — by X-raying. It was found that 30% of the welds had internal cavities and dangerous cracks. Cracks were also found in the H-shaped steel supports. In spite of this, the oil pipe was put into service. On analyzing the accident which soon followed, it was ascertained that thousands of X-ray photographs presented to the client were evidently falsified. But this incident in no way compromises the X-ray method for determining cracks in welds, forge work, heat-treated parts and other articles.

The essence of X-raying is clear to all. We all undergo periodic examination by X-rays. It is very simple. X-rays react primarily to the density of a substance and its ability to absorb radiation. Therefore, if there are pores in the metal they do not absorb the rays and the image on the screen will be brighter. That is how things are with cracks too. A great merit of X-raying is that it does not demand that the surface of the metal be of good quality. That is why it is suitable for welding. Ultrasonics is quite another matter. It is extremely exacting as concerns the quality of the surface. It demands polished surfaces, which is impossible to achieve in mass production and under field conditions of laying pipelines a thousand kilometers long. Therefore, where there is welding, there is X-raying. However, it has its shortcomings: the duration of the process, the need of a photographic dark-room, the danger of exposing the attendants to radioactive radiation. In spite of all this, X-raying is employed because in colossal accidents, in gas pipelines for example, not only are enormous material losses incurred but thousands of human lives are endangered. That is why special investigating groups examine absolutely all the welds, and in case a crack is discovered, the defective part is cut out and rewelded.

There is much truth in the jest from the Soviet satirical magazine *Crocodile*: "Weld defects are removed by cutting them out and introducing new defects." For no matter how good a weld is, unfortunately, there is always a place (if not for large cracks) for very minute cracks which cannot be recorded by X-rays. This does not mean that the weld will necessarily break, but one thing is certain — microcracks will be present in it.

No matter how hard it is to register a crack, it is possible to do so if the crack is motionless. But it is another matter if it is moving, and at a breakneck speed of 1-2 km/s. Obviously, here the only thing to do is to resort to motion-picture filming — to be exact, to high-speed filming. In the simplest case this is how it is done. The optical image of a moving object, for instance a crack, falls on a rapidly rotating mirror which unravels the image on a stationary film. And in order that the exposure should not be blurred, light is directed through a small lens that 'arrests' the image on one spot of the film. There are tens of such lenses; the mirror rotates at a frequency of tens of thousands of revolutions per minute. The frequency of motion-picture filming is millions of exposures per second. The images on the film are separated by intervals of a million fractions of a second. That is sufficient to study the behavior of a rather large crack moving for a relatively long time. But what if we are interested in the fine details of fracture, let's say, during one ten-millionth or hundred-millionth fraction of a second? Then exposure filming is of no use because it is relatively slow, and finer divisions of time are needed.

Therefore the image is simply unravelled on a stationary film by a rotating mirror, without intermediate lenses. Now a good three-dimensional image of the crack is out of the question; only shadows are obtained. But then the recording rates increase at once by a hundredfold. We can now distinguish time intervals of a hundred-millionth fraction of a second.

But if even this is not enough? There is still another way. The reader knows that today the laser has become for science a true hard toiler. It comes to our aid in this case too. The luminescence of a laser can last one billionth part of a second. On being switched on at a given moment, the laser produces a single image of a flying object during that time. That is how images are obtained of the flight of a bullet, missile, meteor or rocket. If not one but many successive photographs are required, a series of lasers are set up that with the aid of electronics, operate in succession at preset intervals.

As we see it is not half so bad if the crack cuts a transparent material. But if it propagates in steel, what then? In this case, at present, there is perhaps only one method available — high-speed X-ray photography. The problem consists in the fact that X-rays do not refract and do not observe the usual law for light that the angle of incidence equals the angle of reflection. Therefore, it is impossi-

ble to unravel the X-ray shadow of a moving object by means of a rotating mirror.

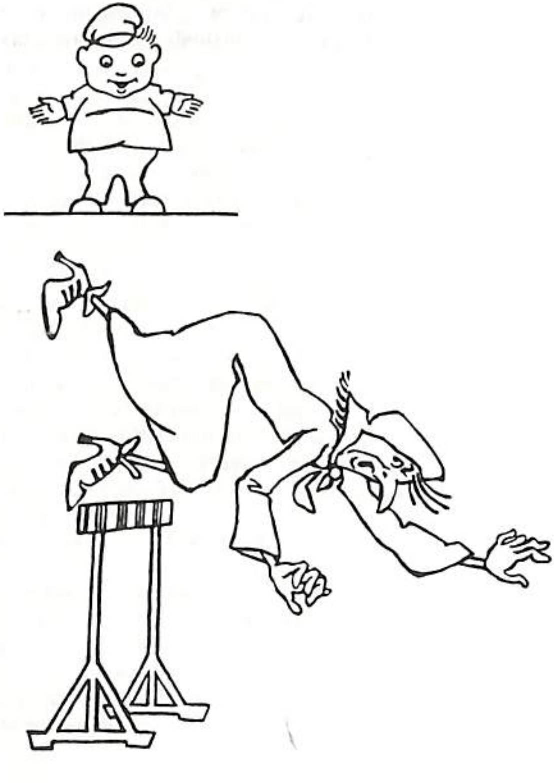
We proceed as follows. Several pulse X-ray tubes are installed that emit an X-ray for every millionth part of a second. The rays from each tube produce a shadow of the object and give an image on its film. The tubes operate by turns and we get five-six separate exposures of the process taking place within the metal. This method is used to study the penetration of a shell into armor or the shape of the front of a crack in steel.

Is this not too complicated for a simple crack? Is it so necessary? Yes, it is. It is sufficient to recall the misfortunes that fracture can bring, to strive to know everything about a crack: the time and place of its birth, its 'parents', the conditions of its growth, and its nature. For all this, methods and instruments are needed.

The crack hides beneath its arrowhead
Like a pinned-down poisonous snake . . .

(After Andrei Voznesensky)

Chapter 3
Crack – Stopping



CAN A CRACK BE BRIDLED?

Against an offensive force
we'll find a self-defensive one.

(After Johann Wolfgang von Goethe)

Now that we are firmly convinced that fracture is an evil it is appropriate to ask: how can it be stopped? How can the propagation of a crack be discontinued, curbed?

In order to understand that this is by no means a simple matter, let us recall some of the properties of a crack. First of all, it moves swiftly, at a rate of several kilometers a second. At such speeds the fracture is brittle and has no need of plastic deformation. Therefore, the crack is content with a negligible amount of energy from the object being destroyed. It is practically free from inertia and that is why it is capable of instantaneously turning in any direction that promises a new portion of elastic energy. Besides, a crack possesses a remarkable property — as it gets older, it grows younger, i.e., it is capable of moving in the metal structure at an ever-increasing rate. It is neither afraid of structures several meters long nor of oil and gas pipelines many kilometers long. On the contrary, the larger the structure, the greater are the chances of a crack to expand. This is the enemy we must contend with. Its weak points are not readily seen, but they must surely exist. Let us look for them.

First of all, the crack is 'nourished' by the elastic energy of the mass under stress. Is it possible for us to control it? It appears that it is, although with some difficulty.

The tip of a crack is very sharp. Therefore, the concentration of stress in it is incredibly high. Is it possible to blunt, to 'behead' a rapidly moving crack? This is not an easy thing to do, yet it is quite possible.

A brittle crack demands very little energy to move along. But does not that mean that very little energy is needed to hinder it? This is so. In this chapter let us use our imagination and search for barriers capable of holding fracture back.

A crack emits elastic waves, including sound waves. That means that in its turn it must be sensitive to waves impinging on it from without. A composer cannot be indifferent to the music of others.

At its tip a crack, even a fast one, produces defects in the crystal lattice. Apparently, this means that it itself is sensitive to such defects. Therefore, there is a chance that they can be utilized as barriers.

Recall the branching of a crack, which reduced its speed. What if?. . .

There are a great number of such flaws in a crack. It is only necessary to carefully track them down. Then it turns out that fracture is not omnipotent. It brings people misfortune yet fracture itself is vulnerable. And we must take advantage of this. The reader may ask: why doesn't Nature itself look after the prevention of fracture? Does that mean that Nature gains something from it? Perhaps that is so — Nature often converts order to disorder. Nevertheless, Pascal, who believed in man's capabilities, said: "Nature does not know how great it is, but we do."

MANICURE WITH AN AX

. . . And lo! — a sudden light through the dark . . .

(After V. Bryusov)

The stopping of cracks only implies that they are retarded, not cured. Therefore, the purpose of preventive measures is limited: to quickly stop fracture in order to prevent impending catastrophe; to gain a few minutes in order to complete an industrial cycle; to repair a mechanical part, for example, to weld a fracture. Therefore it is obvious that as long as there is a crack (even if it be retarded) in working metal, it is unsound, impaired. Just the same, even such a moderate process as crack-stopping is necessary and useful because it prevents accidents fraught with serious consequences and irreparable misfortune.

How can we stop a crack? Evidently by depriving it of that without which it cannot exist. In other words, we try to prevent the birth of the crack. In principle, of course, this is possible, but in actuality it is not. The fact is that incipient cracks are either already present in structures from the beginning of their existence or they appear in the very first stages of operation due to metal fatigue. That means we can hardly hope to attain success in this way. The subcritical growth of a crack and its growth in the supercritical period, however, is another matter. Both these processes demand elastic energy. Is it possible to stop this flow of energy, or at least to convert it to a small jet?

There are three ways of doing this. The first is the most radical one. Is it possible at the first signs of danger to instantaneously unload the entire system which contains the growing crack? That is, 'with one blow of an ax' to chop off the destructive force acting on the damaged unit and to apply it to the reserve metal plates. Perhaps, in some cases it would be possible to do so. But many difficulties would arise. In order to instantaneously unload a system with a growing crack it would be necessary to have a quick-acting device that would react at an incredible speed equal to thousandths of a second and less. And that is still not all. Unfortunately, the fundamental principle that operates here is: 'all-or-nothing'. By all means the whole elastic field must be discharged or, as physicists say, relaxed. Otherwise a sufficiently brittle crack that is 'nourished' by the energy of sections that are not discharged will continue to grow. We know that it needs very little energy to do so.

The following way is much simpler and more practical. Say we are designing the wing of a plane. We proceed from its strength in the monolithic state. It is necessary, however, to take into account a critical situation when a crack appears in the wing. Obviously, this causes many changes. The concentration of stress is now much greater than the calculated one and, moreover, the rest of the wing that is not damaged, and may even be far from the seat of destruction, also adds to the evil done because it supplies elastic energy to the growing crack.

How should this be prevented? First of all, by designing every responsible structure proceeding from its behaviour not only in the monolithic state but in critical situations as well. It is not enough to think of decreasing the stress concentration around the rivets or of reducing stress at the expense of the safety margin. It is necessary to foresee the possible growth of a crack and take measures to diminish the flow of elastic energy to that area. How can this be done? It is

probably necessary to work out a whole system for saving the structure from destruction. It should include the conscious control of the fractures that can always be expected. Nobody says it is simple to do this, but it is absolutely necessary.

Here is one of the ways of finding a solution to this problem. Let us assume that we have succeeded in preventing the crack from passing from the subcritical to the supercritical state. Does this mean that the crack is stopped? Not necessarily. It can continue to grow very slowly. But that means that the energy supplied to the crack by an outside force and the stored elastic energy are spent on plastic deformation at its tip. This is not the best thing, of course, because fracture does take place. Still it is better than explosive and uncontrolled supercritical fracture because we gain time.

How could we prolong the process of fracture as a whole by means of plastic deformation? First of all, it is the job of the structural material. It must be ductile as well as strong. If it is sufficiently ductile, it will put off the moment when a crack will originate. And later, the ability of the metal to deform more readily than it breaks will secure it against the rapid transition of a plastic crack to the avalanche-like stage of frantic destruction descending at the speed of sound. All this time, while the subcritical crack grows slowly, the plastic deformation at its tip converts the elastic energy of the surrounding area into heat, scattering it in the metal and the air. It turns out that here plastic deformation not only plays the role of a buffer that dampens loading, but also that of a valve that

'releases excess steam and thus reduces the pressure'. Who knows? Maybe we could easily stop a crack if we were able to open up the valve at any time. For instance, we sharply reduced the resistance to plastic deformation at the tip of the crack by heating the area surrounding the crack. How can we heat it? That is another matter and we will speak of it later. What is of importance is that with a rise in temperature, the metal deforms much more readily. No wonder metal is rolled and forged when red hot! It is clear that in this case the metal at the tip of the crack will flow much more quickly. More elastic energy will be consumed and the time of fracture will be put off.

Is there any chance of making use of plastic deformation in the supercritical stage of a crack? There is, but very little. The reason for this is that at high speeds of fracture ductility is suppressed — it simply has no time to take effect because too little time is allowed to the sources of dislocations while the rapidly moving crack passes them. Therefore, plastic deformation is concentrated at the very edges of the crack (not thicker than a few tens of microns). If only it were possible to obtain materials in which the dislocation sources were completely free, not blocked by impurities . . . If only it were possible to set them free to generate dislocations instantaneously and in large numbers . . . And if the dislocation sources began to work not at definite stresses but at any stresses, no matter how small, so that they would be able to function away from the faces of the crack . . . Then . . . But there are too many 'ifs', aren't there? At the present time, unfortunately, we cannot count on any considerable plastic deformation near a supercritical crack. Consequently, plastic deformation can be counted on only prior to the appearance of a crack or in the early subcritical stages of its growth. Later it is already pointless to do so.

But is everything actually so hopeless? Of course not. There are many possibilities. Suppose that at the time of designing and constructing a structure, we purposely placed a powerful elastic field in the path of the crack — a simple enough task. How is elastic stress produced in prestressed reinforced concrete? The reinforcement is stretched on a simple machine and in this state concrete is poured on it. When the concrete hardens, it will be under compression, while the reinforcement will be under tension. The strength of such prestressed reinforced concrete, as we know, is much greater than that of ordinary concrete. We can proceed in approximately the same way with a metal structure. Part of it is compressed and a

metal plate is welded or riveted onto it. The parent metal will then be under compression and the plate, or stringer, under tension. When a rapid crack invades the area under compression, the elastic tensile energy that pushes it along is extinguished on the opposite elastic compression field and the fracture, deprived of its nourishment, is stopped. Any kind of crack, even supercritical ones, are thus stopped in shipbuilding and in aircraft manufacturing.

Sometimes in shipbuilding the procedure is different. A groove is cut in the expected path of a crack, and a stringer is riveted above it. Such a barrier is an absolutely insurmountable obstacle for a crack. It is true, however, that in this case as well as in the former one, we ourselves introduce defects in the structure (welds and holes). But this cannot be helped. We must choose the lesser evil.

A 'SANDWICH' STOPS FRACTURE

. . . A second has become infinity . . .

(After Eugene Jebelyanu)

In the preceding section we spoke of a crack and a stringer or a groove. As a matter of fact this is only one of the aspects of the behavior of cracks at an interface. Laminated materials consisting of heterogeneous layers may also be called composites. They resemble sandwiches. But in contrast to an ordinary sandwich, which should be edible, such a 'sandwich' must be 'undigestible' for fracture. It is a preplanned and 'designed' foe of a crack. Sometimes it can sacrifice the strength of one of its numerous layers, but sooner or later the crack will fall for the bait and be caught. The crack in this case also has its 'credo' — it is hardly ever indifferent to the interfaces of media with different elastic characteristics. It either 'loves' or 'hates' them, i.e., it either penetrates through them or not, but it is never indifferent to them.

When a crack approaches an interface it can behave in several ways. First of all, the crack can break through it, losing part of its speed, and propagate in the second material. Practically speaking this method is only partially useful or of no use at all. Of greater importance is when the crack gets stuck at the interface and fracture is stopped. It is also possible that the crack is hindered at the

interface, but then, under the stress acting on it, it ruptures the material along the surface of adhesion. This is quite probable when a crack goes from a soft constituent to a more rigid one.

What are the simplest combinations of media capable of hindering cracks? First and foremost they are alternating layers of tough and soft materials. The former constitute the base — they bear the load; the latter hinder fracture. Such laminates may consist, for example, of a base made of high-tensile alloyed steel and one or two layers of soft low-carbon steel. The method of joining the layers is of great importance. The simplest method is welding. New reliable synthetic adhesives can also be used for this purpose. The crack, on approaching the ductile layer, spends the elastic stresses at its tip on plastic flow. This inevitably leads to retarding the crack or stopping it completely. Also, in the process of flowing, the radius at the tip of the crack grows larger — it becomes more blunt. And it is well known that the stress at the tip of a blunt crack is less than that at the tip of a sharp one.

It is not absolutely necessary for the laminate to consist only of steel. Metal 'sandwiches' can be constructed, for instance, from steel and copper. The steel constituent imparts strength to the structure; copper protects it from possible fracture. A crack generating in the steel layer always gets stuck, or as we say, is localized in the copper layer. The toughness of such a bimetal is much greater than that of ordinary steel.

What truly fantastic possibilities there are for matching up pairs: plastics and wood, a monocrystal and a polycrystal, steel and resin. And what a future for the 'collaboration' of iron and glass!

It is not at all necessary that there be two layers. There may be many layers. For example, six layers of beryllium alternate with five layers of aluminium. In contrast to monolithic beryllium, which breaks at once along the entire cross section, such a 'sandwich' breaks layer after layer and therefore can withstand a load that is 5-6 times greater. 'Sandwiches' are especially efficient when the load is a dynamic one. This is easy to understand since in rapid loading an important role is played by elastic waves that not only act on the given unit but also push the cracks ahead. Moreover, the interfaces refract, reflect and sometimes disperse the flow of waves. That is why in laminated materials the propagation of waves is more complicated, which is advantageous to strength.

But the barrier properties of multilayer materials is only one of their positive characteristics. There are others; for example, if the material is compressed prior to gluing the layers, the birth of incipient cracks in it is hindered. Moreover, because of their small dimensions the thin layers of high-tensile metal of which it is composed are, as we know, less subject to brittle failure than the same metal in the monolithic state. Of importance, also, is the fact that they are in a state of spatial stress which suppresses fracture.

Up to now, when speaking about the interface of different materials, we have had in mind its adhesive and barrier properties. Its influence can be much greater. An interface can generate compressive stress fields on both of its sides. We know that a crack is

afraid of such fields and soon stops in them. This property is often made use of in shipbuilding. Welds are superimposed in certain crack-dangerous directions even on steel of one kind in order to produce extensive elastic compression fields. Such welds are even more useful for joining different kinds of metal. However, all is not as simple here as it may seem. Just any kind of weld is not suitable for this purpose. Some welds accelerate cracks instead of hindering them.

In any case, by consciously controlling the fields of elastic stresses in the immediate vicinity of the interface of layers, a crack can be forced to turn at an angle to the plane of the interface and move along it, i.e., in a direction that is not dangerous.

Of interest are complex 'sandwiches' in which the crack grows in the direction of the layer but its plane is perpendicular to the plane of the layers. Here a mechanism sets in resulting in the separation of the material into layers. This is bad, of course, because fracture takes place. On the other hand, such a formation of many cracks leads to rapid hindering of the main crack (the energy of the many simultaneously opening surfaces is very great indeed). Still present-day 'sandwiches' are, as a rule, afraid of cracks that go along interfaces — that is a vulnerable direction. A 'sandwich', like a warrior of old, strives to place its shield (i.e., the interface) under the direct blow of the sword. Yet, theoretically, a crack propagating along the line of adhesion does have a hindering effect. The fact is that the stresses at its tip are not constant but pulsating, i.e., they repeatedly change in space and time. As a result the faces of the crack, that is the layers of different materials, should overlap one another. They cannot actually do this, therefore it is only a question of adjacent layers mutually pressing into each other. Unfortunately no one has as yet checked this experimentally, although if such a thing did take place it would not only be of theoretical interest but also of practical importance. It would mean that the crack was deprived of the possibility of moving freely between the layers because of the varying stresses and the extremely complicated trajectory of its movement from dent to adjacent mound. But the possibility of such an effect has as yet to be proved — it is far from being universally accepted.

At times the interfaces do not act only on a crack that crosses them or on fracture in them. A crack in a multilayer laminate can be situated inside a layer and be parallel to the interface. In this case the behavior of the crack will not be simple. For instance, if the ad-

jacent media are more rigid, the crack will tend to move in the middle of its soft corridor. However, even here its movement is unsteady and its path is a smoothly undulating curve.

I believe that the ironical words of the American writer Jones could refer to a fast supercritical crack: "Let it be a road that leads nowhere, but there is a green light all the way." Composite laminated materials play the role of a red light that stops a crack not only figuratively but physically as well. This is probably the simplest and most reliable way of stopping fracture. It is true, however, that it is not always the most economical and expedient way — because of its comparatively high cost and because at the present time far from all structures can be made of sandwich-like materials. However, where this is possible, multilayer materials reliably stand in the path of fracture, guarding the strength of the structures.

LET THE CRACK BURN!

. . . A cobweb in transparent air
Cold as a crack in glass . . .

(After Novella Matveeva)

Is a crack really cold? Yes, if it is motionless. But it would be wrong to say so with respect to a rapidly growing crack. The reason for this is that heat is generated when atomic bonds are broken at the tip of the crack. Besides, in the end, the plastic deformation that takes place there leads to the evolution of heat. If fracture takes place fast enough, these processes proceed at an increasing rate. Moreover, there is not sufficient time for the exchange of heat between the crack and the mass of cold metal, and heat accumulates in the place where it is evolved. Therefore high temperatures can be expected in the vicinity of the surface of a crack and at its tip. Hence, the essential thing is the adiabatic (high-speed) character of the process of fracture. The reader knows, of course, that all adiabatic processes unfailingly lead to a rise in temperature; for instance, when fuel explodes in the combustion chamber of a diesel engine; when a bullet hits an obstacle; when air is rapidly compressed in a pump, etc.

Thus, in principle, there is no doubt that heat accumulates at the tip of a crack. Indeed, theoretical investigations have shown that the temperature that can be expected in steel, for example, can range from 100°C to 700°C. In practice, however, everything is much more complex. It has not been possible to register such a rise in temperature in experiments on metals. The point is not that heat is not generated, but that it is very difficult to record it, because the rapid change in temperature must be measured in a space several square micrometers or less in size.

Nevertheless there can be no doubt that some heat is generated at the tip of a crack. Still it is clear that it does not seriously affect fracture, although it would not be a bad thing if it did. Suppose that a fast crack heated its own tip to such a degree that the material almost became fluid and brittle failure was stopped.

For us such a self-stopping fast crack is very appealing. It would be verily suicide! Unfortunately a crack is too self-assured, too much in love with itself to commit suicide. Hence, it is we who must deal with this evil. And for this purpose we can make use of the same factor — heat — but heat intentionally brought to the place of fracture from without.

The effect of high temperatures on a crack is favorable for many reasons. For one, the ductility of the metal increases with the temperature and ductility is capable of reducing the speed of fracture. In addition, the crack being a break in continuity markedly changes the heat flow produced in the metal from an outside source. This causes a change in the temperature distribution at its

tip and the appearance of thermal stresses. The problem as a whole is quite complex.

Let us try, with no recourse to the serious mathematical analysis necessary for its solution, to understand the nature of the effect produced by the interrupted heat flow. Its essence is simple; the crack conducts heat poorly. Therefore the temperatures at its two faces are different. But we know that metal, on being heated, expands. Consequently, the faces of the crack expand to different degrees. And these two dissimilar heat expansions meet in the common tip of the crack. If the crack behaved like the bimetallic plate employed in gas columns, both its faces would bend. The metal plate with the greater expansion would bend more than the other one, resulting in the formation of a comma. But a crack is not a thin plate; it is only part of a solid mass of material. Consequently, it tries to bend, but the main material does not allow it to do so. As a result thermoelastic stresses are produced in the mass of the material. They interact in a complex manner with the stresses resulting from an externally applied load. Such a situation, under certain conditions, can speed up fracture but under other conditions, hinder it. The problem consists in finding these conditions and making use of them.

In the case considered above, the crack would deflect from the source of heat. However, the opposite can take place. Let the source of heat be located far from the crack — so far away that the surface of the crack is not heated. Then fracture is affected only by the thermoelastic stresses that always surround the heat source. The mechanism is very simple. The source heats the adjacent part of the metal and expands it in the radial direction. The crack situated at a tangent will be compressed. It can no longer grow in this direction and is forced to dodge. But how? Let us recall how a glass with hot water expands. In the same way the material surrounding the heat source expands. Here, along the generatrix of the cylinder with the heated core, tensile stresses arise in the material, that tend to burst it. A crack, as we know, is very fond of tensile stresses. Therefore it will rush to the spot that is being heated, greedily devouring its 'food' — the field of tensile thermoelastic stresses.

Direct experiments have shown that as a rule, a crack propagating in the vicinity of a heat source turns abruptly to it, then wedges into the fused zone and stops.

Sources of negative temperatures afford additional possibilities. Here the crack declines from the cooled zone and moves at an in-

creasing speed. By arranging the heat sources in a definite order, say staggering them, so that their stress fields cross each other, the trajectory of propagation of the crack can be arbitrarily led away in any preset direction. The motion of the crack can be hindered, completely stopped or, if so desired, accelerated.

Can all this be utilized for hindering a fast crack? Yes, it can. And this is how. First of all it is possible to create stable thermal fields in the path of fracture advancing at a rate of 1 000-2 000 m/s. If the crack moves in the direction of rising temperatures, sooner or later it will stop. It is possible, however, to proceed as follows: not to produce thermal fields beforehand, but to wait until fracture begins in this area or a crack approaches it. And then . . .

Can an electric coil then be switched on to heat the metal and create a thermal and thermoelastic field in it? It is possible. But by the time we manage to do this, fracture will have already taken place. The fact is that here time is measured in milli- or microseconds. Heating therefore must be quick as lightning and pulse-like. At the present time it is accomplished with the aid of a so-called explosive wire. From a bank of capacitors a powerful electrical charge is passed through a thin wire or foil. The Joule heat produced is so great and is evolved in such a short time (a few tens of microseconds) that the wire cannot withstand it and explodes. The resulting pressure is equal to tens of thousands of atmospheres and the temperature rises to tens of thousands of degrees. Suppose that such a wire exploded right in front of a rapidly propagating crack. Before that the crack 'ran', urged on by tensile stresses, and easily tore the metal asunder.

. . . But a red-hot wire of lightning
Burned through the black cloud . . .

(After L. Ozerov)

The tip of the crack found itself at once in the center of the explosion where almost simultaneously it was subjected to the action of a shock wave, thermoelastic stresses and the ductility of the heated, therefore easy-flowing, metal. As a result, in 10-15 microseconds the crack lost its speed of 1 000-2 000 m/s, became blunt and got stuck. In the same way it is possible to divert a crack from its main direction, i.e., to control it.

Of course, the explosion of the conductor does not improve the quality of the metal — it rivets the latter, producing microfractures in it. Still, it hinders the crack and stops fracture.

Do we have the right to turn to the aid of an evil in order to conquer a greater evil? I think we do. At the cost of this local damage we rescue an entire structure. So it turns out that in this case Petrarch's 'thesis' that

Fire does not set a limit to fire . . .

has become obsolete.

Recall how fire is fought with fire in the case of another disaster, a forest fire. Why not employ this method as an antidote against fracture?

WAVES CAN HINDER CRACKS

Let winds be shrill, let waves roll high!

George Gordon Byron, *Childe Harold's Pilgrimage*

A recent Soviet film showed how in a certain mountain region an attempt was made to stop drilling and blasting which might have caused valuable monolithic granite and marble to crack. It is clear that the cracks would have been caused by elastic waves arising at the site of the explosion, and propagating quite a distance from it. That does not surprise us. Every volcanic eruption produces waves that can encircle the Earth several times and sometimes cause incredible destruction. Hence it is not hard to understand that elastic waves are not only capable of calling forth the appearance of cracks, they can also decidedly affect the character of crack propagation.

What kinds of elastic waves are there? Usually three kinds are distinguished: longitudinal, transverse and surface waves. Besides that they are subdivided into transient and maintained waves. Maintained (authentic) waves are those with crests and depressions (maxima and minima) repeated many times. In such waves elastic disturbances follow one another in endless succession:

. . . Wave after wave
Like horseman
After horseman . . .

(After M. Kvlividze)

In a longitudinal wave of this 'continuous' type a substance is compressed in the direction of the propagating wave. Let us assume that the wave is incident at right angles to the plane of the crack. It will obviously compress the faces of the crack and hinder fracture. But what if the wave propagates along one of the faces of the crack, towards its mouth? Then this part of the material will be compressed and the crack will deflect from it. Between these two cases there can be countless angles of incidence of waves on a crack. By changing them it is possible to alter the way the elastic disturbances affect the propagation of a fast crack. Fracture generally behaves as follows: the crack tends to move in the direction of compressive impact.

Now let us assume that the wave, as before, is longitudinal but under tensile stress. Then in the case of normal, i.e., perpendicular incidence on the surface of the crack, additional extension would result and fracture would be accelerated. Should such a wave propagate along one of its faces, the crack would turn in the same direction. At an arbitrary angle of incidence the crack will always be oriented at right angles to the direction of the expanding wave.

Now let us consider transverse maintained waves. Transverse shear stresses appear in them, so in the great majority of cases these waves, one way or another, turn the fracture around.

Thus, all maintained waves actively affect the motion of a crack and are capable not only of hindering or accelerating it, but also of reorienting it at their will.

By the repeated introduction of energy in the vicinity of the tip of a crack a wave can, on prolonged contact, not only change the stress field but can decidedly alter the trajectory of fracture.

This is especially true for surface waves that propagate in the plane of the crack itself. We have already pointed out that with increasing distance they do not attenuate as quickly as longitudinal and transverse waves do. Besides, waves that move along a crack as along a waveguide deliver all their energy directly to the tip in contrast to longitudinal and transverse waves whose fronts only partially approach the mouth of a crack. Consequently, the efficiency of a surface wave is greater. How does a crack react to the appearance of Rayleigh waves at its tip? If these waves propagate 'nose to nose' along the faces of the crack, fracture will be speeded up in its plane. It is quite another matter if a wave 'flows' along one of the faces. The particles in it vibrate in the plane perpendicular to the surface of the crack, each of them moving along an ellipse, just like in a wave on the surface of water. No one ever wonders why the sea throws objects out on the land. If the particles moved only up

and down this would not happen. That is why in a Rayleigh wave there arise shear stresses at right angles to the velocity of the crack. An experiment conducted by I. S. Guz and the author on a crack with a velocity of 1 km/s showed that it deflected by an angle of 80-85°.

It should be mentioned here that there is still another kind of wave — curved waves. They are formed most frequently in solid bodies. Various parts of aircraft, crane arms, parts of bridges and machines are often subjected to such stress. All the waves previously considered by us increased the stress concentration at the tip of a crack. With curved waves it is another matter. They reduce the stress at the mouth and in this way hinder the crack. And at the same time, just like transverse elastic vibrations, curved waves deflect fracture from its initial trajectory and turn the crack around.

In practice very many waves are of sufficiently high intensity to noticeably affect the birth and propagation of cracks. Thus, fracture of aircraft tail structures often commences under the effect of the great noise and flow of sounds created by the engines.

The range of elastic frequencies generated in structures of a modern jet plane extends from those of infra (audible) sounds (amounting to several hertz) to those of ultrasounds (amounting to millions of hertz). The consequences are drastic: the casing of the elevator gets out of order, which is a direct result of the noise produced by the booster jets. The American press pointed out that similar fracture, also connected with powerful noise, appeared repeatedly in the *Titan* rocket built in the USA.

In the Anglo-French *Concord* supersonic plane the range of maximum sound intensity is from 100 to 1 000 Hz; in the tail of the fuselage, the 100-250 Hz section of the spectrum predominates. It is of interest that when testing parts of aircraft, powerful loudspeakers with special horns are employed. For thousands and thousands of hours sounds act on the objects under test to complete failure of the metal. Use is made of the fact that the crack reacts to a great number of vibrations of various frequencies, especially to the resonance frequency that depends not only on the structure itself but on the length of the crack too. It appeared that these resonance frequencies were in the particularly sensitive range of 100-250 Hz.

All these examples are of interest not because noise is capable of fracturing even metal. On the contrary, we tried to find out how to

make use of elastic waves of various kinds in order to consciously control the trajectory of a fast crack. How can we hinder fracture with their aid? Are maintained elastic waves suitable for this purpose? Unfortunately in practice they are not employed, and for the following reason. Suppose a metal structure is closely guarded by sensitive acoustic, electromagnetic and other devices. All of a sudden a crack appears in it which immediately sends a signal that is noted by the transducers of the 'emergency service'. With the aid of small computers they determine not only the location of the crack but its direction and velocity as well. Then a pulse 'distress signal' is sent out. This signal triggers miniature explosive devices that send elastic waves to the mouth of the crack. How much time have these devices at their disposal? Hardly any at all — only 1-5 μs. Many wave periods cannot be sent in an instant. This means it must be an elastic pulse and not a periodic wave. Only a pulse will attack the crack in a given spot at a definite angle.

What happens to the crack in this case? There are only two possibilities: it must either stop or change its trajectory in the direction we desire. Of course, it is good to stop fracture — that means a catastrophe is avoided and priceless time is gained that is needed for repairing the structure and restoring its ability to serve. But will the crack that has been stopped begin to grow again? It can, but it needs a considerable portion of energy from without in order to do so. Therefore it is desirable to decrease the stress concentration at the tip of the stopped crack as much as possible. This can be attained as follows. When a charge of trinitrotoluene (TNT) explodes it forms a hole in the material of an order of a few millimeters. The stresses produced around it are such that a crack passing by, as a result of the attack of shock waves, turns around to the seat of the explosion and stops in it. This is very convenient because now the radius at the tip of the crack is enormous and the crack cannot grow any more at the stresses existing in the structure.

In this respect another variant is perhaps even better. Let us suppose that the waves turned the crack in the opposite direction or directed it in a circle or helix. Such fracture cannot progress because the stress at its tip will be determined by the curvature of its trajectory and not the sharpness of the tip of the crack. A specimen with such a crack will be as strong as a completely whole one. It can still serve successfully for some time.

What happens to metal when a charge of TNT (or some other explosive) explodes on it? Of course the resulting elastic waves stop

the crack but they also inevitably damage the structure — introduce new holes, incipient microcracks and many other flaws. Still there is no other way; the structure as a whole was in a state of agony. If we failed to stop the crack, fracture would be inevitable.

CRACKS AND CHESS

Perform a good deed: clash an evil with an evil.

(After Victor Zhemchuzhnikov)

We have already spoken about the fact that a crack does not like solitude. As a rule there are a great many cracks in metal that form large groups. Each crack in itself may be insignificant. But almost every crack dreams of becoming a 'general', i.e., the main one. Therefore it deals with its 'fellow' cracks in two ways: on growing it swallows the others or, by reducing the stress in the surrounding area, forces them to 'flop' or vanish altogether. Such a sweet gentle thing, isn't it?

In this chapter we will attempt to look into every possible means, idea and even opinion, even the most fleeting allusion to ways of coping with fracture. That is why we will not be fastidious and will gather all the grains and crumbs of hope associated with this problem.

A group of cracks certainly weakens a body. Of course it would be better without cracks than with them. But as, unfortunately, they cannot be excluded from a metal, let us see if there is a chance of arranging them in such a manner that on facing each other they cancel their mutual evil. Could the interaction of cracks in such a system be a small compensation for a big misfortune? The question comes down to the following: does a group of cracks weaken a body to a greater degree than a single crack? Could it turn out that a system of many cracks would be 'bound' and incapable of rapidly destroying a structure? Finally, doesn't strength prefer to have many enemies rather than a single one because many of them would prevent each other from impairing it?

Apparently, these hopes may well be justified. Ya. B. Zeldovich, a member of the USSR Academy of Sciences, once predicted that in the case of a checkered arrangement of cracks the structure should be strengthened.

Mechanics-theoreticians undertook the solving of this problem and have obtained many interesting and tangible results in the last 20 years. V. V. Panasyuk and L. T. Berezhnitsky of the USSR found that cracks lined up consecutively, one after the other, weaken a body and reduce its strength. That is why such systems are dangerous and must by all means be avoided. This conclusion was reached for motionless cracks, and is all the more true for growing cracks that readily unite.

A system of parallel cracks is an altogether different matter. V. Z. Parton, V. V. Panasyuk and their students made the necessary calculations. First, of all, it turned out that definite mutual arrangements of cracks lead to the stabilization of each individual crack and the system as a whole. This is connected with the interaction of the elastic fields of the cracks, which is more intense when the distances between the cracks are small and they are intimately united. In this case the strength of a body with a system of cracks is certainly greater than that with a single crack.

Did the assumption made by Zeldovich prove to be true? Yes and no. As a matter of fact a system of parallel cracks is preferred to a single crack. However, as far as their checkered arrangement being the optimum one — here a 'but' appeared . . . It turned out that such an arrangement did not assure maximum strength. Metal in which the cracks are lined up in parallel rows and are arranged strictly one above the other is much stronger. There can probably be many rows of this kind but they are not arranged like on a checkerboard, rather like a body of troops forming a square.

Well, and if in a system of cracks the distance between them is great? Then interaction is small and the strength of a body with such a system is still lower than in the case of a single crack. Therefore such an accumulation of cracks is undesirable.

Similar considerations helped some FRG experts to work out a ceramic material of high strength for manufacturing turbine blades. The ceramics are based on powdered zirconium oxide and aluminium oxide which, after pressing them, are baked at 1 500°C. As a result of subsequent rapid cooling extremely small cracks with a diameter in the range of millionths of a centimeter appear. These microcracks subsequently cancel the stress from impact loads and prevent the origination of large cracks in the ceramics.

HOPE IS MY COMPASS

Light — nothing else . . .

(After B. Okudzhava)

My dear reader, in the first half of this book we sowed the seeds for understanding the nature of fracture. Now that they have germinated, and harvesting is in full swing, we must not lose even a single kernel of hope of suppressing cracks. This is not merely a whim but a vital need in this world of machines, mechanisms and structures, upon which not only our civilization depends, but at times, our very life.

A crumb of optimism can be found in the seemingly irreversably destructive process of branching. Of course, the breaking up of cracks into many converts previously monolithic metal into a heap of debris and leaves no hope of extracting anything useful from the resulting chaos. However, if there is only one branching crack, and very often there actually is only one in the metal, then . . .

Then we should recall that in every case of branching the crack loses speed and sometimes even stops.

Could we make use of this circumstance and influence branching every time this is necessary?

But in the first place, when is this profitable? It is obviously unsuitable, for example, in the case of hardened steel. On being retarded after branching, the crack will instantaneously pick up speed once more in such a material. The metal is very brittle and the acceleration of fracture is great due to considerable internal stresses. Ordinary steel that has not been hardened is quite another matter. So is steel that has been tempered after hardening. The internal stresses in it are relatively small. The metal is very ductile and the energy necessary for accelerating the crack is greater than in hardened steel by one or two orders. Therefore, if branching is intentionally produced in such steel, the crack having lost its speed will not be able to make up for the deficiency in its kinetic energy at the expense of internal stresses in the metal. On the other hand, the crack will need much energy for speeding up its propagation and it will have to draw it from the system's reserves of elastic energy (strain energy). And much time is needed for this.

As a matter of fact we employed the well-known ruthless princi-

ple of sambo-wrestling: when your opponent stumbles, push him down; when he attacks, pull him down. In order to stop a fast crack we made it produce, instead of one crack, a whole bunch of them. Of course, we paid a very high price for this: to stop an impending disaster we laid the foundation for two new ones in the future. But that is for the future. As for today . . . Today in our arsenal there is an additional method of hindering fracture.

This method, notwithstanding how controversial and complex it may subsequently turn out to be, has opened a window onto the spring-time world of hope, although the situation is far from simple.

A fast crack is an unstable system. It constantly tends to roam from side to side; it is unscrupulous and unrestrained by inertia, and this increases with the speed of propagation. Under conditions close to those of branching these processes make a crack 'easily hurt', vulnerable in respect to any external dynamic force. It is not at all necessary that it be a considerable one. When a system is not stable it is easily unbalanced. Even a small force is sufficient to bring about branching.

Therefore the problem of branching does not consist in whether or not it will hinder a crack. That is indisputable. The important thing is how to do it. The simplest way is the interaction of the crack with a compression pulse. In ancient Greek tragedies in which it was difficult to unravel the plot by conventional, 'human' means, the dramatist turned to the aid of a device called *Deus ex machina* (*God from a machine*). Literally, this means the intervention of one of the gods who arrives on the stage by means of some mechanical contrivance. The role of such a *Deus ex machina*, in our case, can be played by an elastic compression pulse directed perpendicularly, or at an angle, to the crack. In this battle it is the pulse that always wins because the unstable crack does not require much to be conquered and 'the sting of a bee' (the pulse) virtually always changes the course of the crack and leads to instantaneous branching.

By means of this or any other pulse method it is not difficult to upset the stability of a destructive, rapidly growing crack and to compel it to branch, thus losing speed. This process, when successively conducted at a distance of a few millimeters or centimeters, would make it possible to stop any crack.

Let us suppose that fracture has been stopped. Luckily for us, whereas one crack can grow in ductile steel, in our case there is a group of cracks . . . What can we expect from such a structure in

the future? Its 'life', i.e., its contrived existence, created by us, is only a prolonged event. This is life in which destruction has penetrated so deeply that it has become unreliable — the structure is at its 'last gasp'.

Fortunately, in this case we have a weighty argument that allows us to affirm that there are still chances for salvation — indeed many of them. The fact is that in order to speed up, a crack has to spend energy on plastic deformation at its tip. It appears that at low speeds, plasticity is great, but with an increase in speed it falls rapidly (approximately in inverse proportion to the square of the speed). Therefore if a crack, due to branching, has been hindered or stopped, the force necessary for its further growth will be nonlinearly great. All the more so because in one area there will be not one crack but two or three. Now in order to grow they will need a quantity of energy that greatly exceeds that needed for the growth of a single crack. That much energy may not be available in the system and a body with a network of cracks may be sufficiently strong to withstand fracture for such time as is needed to do repairs. Of course, we would prefer a monolithic airplane wing to one with a system of cracks, but what else can we do if fracture has already begun? In this case any means are good if they prevent a misfortune. And in this situation we differ very little from the unknown general who rallied his forces with the words: "We have no white flag and therefore we are obliged to win."

FLAWS ACT FAVORABLY

And in this battle, an evil
Is vanquished by a greater evil . . .
(After M. Voloshin)

All the means and methods of hindering fracture that we have described up to now have one thing in common — they are all macroscopic. Moreover, we actually committed an act of violence upon the metal by stopping cracks in it with the aid of elastic waves, thermal and thermoelastic fields, and finally, by using other cracks. Composite materials were the only exception. They were given a chance to 'have their say' in order to hear the 'opinion' of the

material itself. But, of course, this was inadequate because ordinary metals did not take part in the discussion, whereas their 'opinions' are of great interest to us. Crystals have their own ways of hindering cracks — their own reserves and quite a number of them. How can a crystalline material oppose a crack? With its strength? Yes, but that is a general term that expresses nothing. Its plasticity? Certainly, but this is too general also.

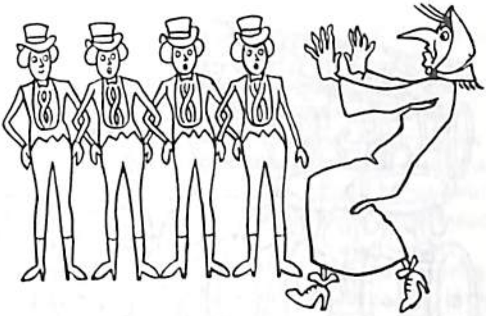
The really true relations of metal to fracture is manifested in the actual barriers which it can put in the path of fracture. Figuratively speaking, what soldiers, regiments and battalions can the metal move against the advancing column of hostile cracks? The ranks and files of defects in the metal constitute its troops of self-defence. This army consists of soldiers — dislocations. It is they, these military forces of the metal, that must take upon themselves the first blow dealt by a generating and then growing crack.

Thus, the internal defects of the material turn out to be the chief hope for its strength. Let us turn our attention to the 'queen' of defects — dislocations. We remember that there are two 'sisters' — edge and screw dislocations. Experiments have shown that a single edge dislocation and a crack are completely indifferent to each other.

They are mutually indifferent even when a crack crosses an edge dislocation. The relations between a screw dislocation and a crack

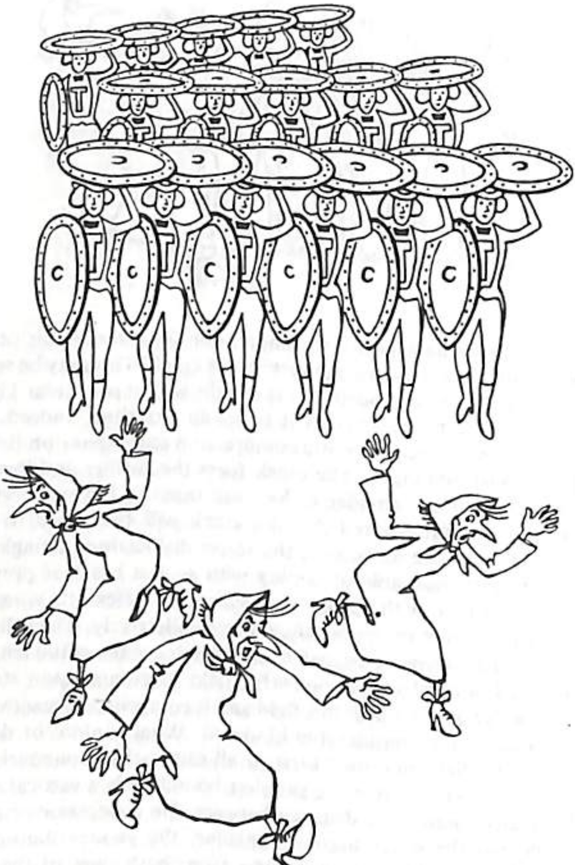
are altogether different. The main point here is that this dislocation twists the crystal into a helix. This means each crystallographic plane is also converted into a helix. Neither does the fracture plane escape this fate. And where there is a helix, there appears a threshold joining parts of the plane of different levels. As physicists say, steps appear when a crack reacts with a screw dislocation. But this means extra surface and, consequently, additional surface energy. To form a step the crack is obliged to borrow elastic energy from the 'bank' whose 'president and institutor' is the destructive force. This means that to overcome a screw dislocation the crack has to exert additional, though very small, effort. If the 'bandit' crack encounters a single screw dislocation, the latter will not be able to offer noticeable resistance. It is quite a different matter if there is a legion of dislocations. Then they transform the parade procession of the crack into convulsive galloping from one bump to another. To overcome the resistance of small but numerous opponents, the crack has to turn thousands of times to the 'bank' for subsidies. The resources of the bank, however, are limited. The available currency, i.e., energy, is scant. If the number of screw dislocations is great enough, sooner or later, there will come a moment when the bank will become insolvent and in the twinkling of an eye the crack, having lost its ardor, will come to a stop, as it always lives on credit.

Are many dislocations needed for this to happen? Unfortunately a very great number — billions and billions and billions. Metal does not always have so many at its disposal. Therefore we must not rely too much on this way of hindering cracks in metal although it certainly plays a positive role.



Perhaps we have gotten the impression that an edge dislocation is a coward since it evades battle with the crack. This may be so, but only because we demanded that it fought with a particular kind of weapon, say rapiers, whereas it excels in wrestling. Indeed, each edge dislocation creates elastic compression and expansion fields in the area surrounding it. The crack fears the former and loves the latter. Therefore if an edge dislocation turns to the crack with its shield, the compression field, the crack will be forced to stop. However, just like its 'sister', the screw dislocation, a single edge dislocation is incapable of coping with such a beast of prey as a crack. A 'round' with a crack proceeds quite differently when edge dislocations unite to oppose the danger collectively. Then they are capable of creating an extensive line of defence the entire length of which is bordered with a powerful field of compression stresses. The crack cannot by-pass this field and is compelled to react with it, its motion being considerably hindered. What 'union' of dislocations do we have in mind? First of all dislocation boundaries.

It is well-known that the simplest boundary is a vertical row of edge dislocations. The distance between the dislocations standing one behind the other becomes smaller, the greater the angle at which the crystals are turned away from both sides of the boundary. On closing their ranks, the dislocations resemble the 'turtle' formation of Roman warriors. A compact solid mass of shields with a palisade of spears meets the enemy. In approximately the same manner the dislocations surround themselves with a wall of compression fields that have united into one rug — even in two rows. At distances of 1 000 μm a field of internal stresses is formed due to crystallization of differently oriented grains; and in the



vicinity of the dislocations themselves, their own elastic field is extended only a few interatomic distances.

In a monocrystalline material even such a uniform boundary between subgrains can affect a slow crack, although it cannot hinder a fast one. But in polycrystalline steel the grains are turned about to such a degree that they sometimes form a great many of such rows. If the angle of inclination formed by adjacent grains reaches 30°, such a boundary is invincible; a crack cannot force its way through it.

Parallel rows of 'Roman turtles' stop a crack moving at any speed and supplied with any amount of elastic energy. If the boundary is twisted like a screw (a screw boundary) and is 'constructed' of screw dislocations, it is still stronger. This is easy to understand: besides the fact that the elastic fields of the dislocation walls act, any breakthrough is accompanied by the formation of steps, and that means an additional loss of energy. That is why even a 20°-screw boundary is a barrier that is altogether insurmountable for fracture.

That is how things are when we conduct experiments in the laboratory with a single boundary between two crystals. Physicists call such a pair a bicrystal. But in actuality everything is much more complicated than in the laboratory — in the end steel is inevitably fractured by a crack. Steel actually consists of tens and hundreds of thousands of crystals. How does a crack defeat a structure? How does it

> *. . . Through a forest of crystals*
> *pursue its course, stopping*
> *at nothing? . . .*
>
> (After V. Shefner)

First of all these thousands of crystals are disoriented in different ways. A great many of them are hardly turned with respect to each other. Many are turned at great angles. There are unlimited possibilities for such an experienced destroyer as a crack. Let us assume that at the given moment, its opponent is a small-angle boundary. It breaks through comparatively easily and the fracture emerges on a wide-angle boundary. A blow, another attack . . . It does not succeed in breaking through. But the crack is under constant external stress. If it is a slow crack it has time for preparatory bombardment. It begins to deform the metal at its tip, saturates it with dislocations, alters its structure, turns aside the crystalline

grains in front of it and, in the end, breaks through the mutilated material. If it has no time, it proceeds otherwise. It turns about quickly and goes to another boundary of the crystalline grain that is more favorably oriented. We have already spoken of how unscrupulous a crack is, of its great maneuverability and ability to change its path. That is just what it does. A method based on trial and error. Rapidly gaining experience, which according to the wise men of the East is often the child of mistakes, the crack finds the vulnerable spots in the defence of the polycrystal and breaks through one boundary after another. Of course a crack is not a living being; it is not even a substance. Therefore we can speak only rhetorically of human experience. Physically it is something like this. On meeting a barrier and not being able to break through it, the crack is obliged to turn about and move to the nearest cleavage plane. What happens is the same as when you press too strongly on a pen. It becomes unstable and deflects. The crack also deflects, only at a definite angle. Now it presses on a different part of the boundary. If the place is suitable the crack will break through it. If it is unsuitable, the crack will turn once more. It is as if the crack probes various parts of the boundary until it finds the most vulnerable spot in it. In the end, statistics (Muse of summation!) sometimes favors triumphant fracture. The mass of steel is of widely varying strength and there are many small-angle loopholes for a crack in it.

If we could only shut them off. In this respect the points where the boundaries of three grains meet are very promising. They turn out to be hard nuts to crack for any crack, including extremely fast ones. There are several reasons for this. First of all a triple joint is where three vertical rows of dislocations come together at one point. It should be pointed out that up to the present time we do not know just what takes place at this point. How are the atoms displaced there, what has happened to the crystal lattice? That is why we cannot say anything definite about the nature of the interaction between a crack and the triple joint itself. We can, however, picture what takes place on withdrawing, even slightly, from the geometric point of the joint. A triple joint is surrounded by two kinds of stresses — thermal and elastic stresses from the dislocations in the walls. Both kinds are much greater than at ordinary boundaries. And the important thing is that they spread considerably farther. For example, dislocation stress fields occupy an area ten times that of an ordinary single wall. No wonder that these

stresses, which begin to act earlier, hinder the crack more effectively. But this is not all. The stress field in the vicinity of the joint is so complex that the crack which in an ordinary monocrystal is accustomed to being situated along the cleavage face, here disintegrates into a great number of tiny cracks not even necessarily positioned in the cleavage plane. It is compelled to turn sharply, to move in curved paths, to branch. In short, little is left of the previously monolithic crack. In these conditions the crack that is (in the words of the poet Mandelshtam) 'starved for cleaved space' is transformed from a beast of prey to a victim. It resembles a foaming mustang saddled for the first time, rushing round and round in a cloud of dust. It still hopes to tear the bit but has already lost its freedom forever. The force to destroy and harm still rages in it, but it, once saddled, can no longer hurt people.

No wonder, therefore, that all the cracks are hindered at the joint of three grains. The only trouble is that a crack seldom runs up against the joint itself. More often it passes the joint by and is not affected by the latter.

However, dislocations can line up not only one behind another, they also form ranks 'shoulder to shoulder', as if joining hands. That is the way they are arranged in slip planes. The extra planes of all these dislocations are frequently directed similarly. In other words, they can be dislocations of the same sign. In this case compressive stresses predominate on one side of the slip plane and tensile stresses on the other. Obviously, therefore, if the crack approaches the slip band from the compressed side it is bound to be retarded. Otherwise it can be accelerated. However, on passing through such a band the crack finds itself in an area under compression . . . Experiments show that on the whole slip bands of any orientation have a hindering effect on a crack. Fracture, as in the case of intergrain joints, ceases to be monolithic and disintegrates into numerous minute cracks, then turns along the band and propagates parallel to it. Sometimes it is even capable of turning backwards! In order to break through a slip band it is absolutely necessary that the crack borrow and spend elastic energy.

A crack is disastrous only for one or a few slip bands. Systems containing tens and hundreds of bands are not afraid of the crack and stop it. Bundles of intersecting slip bands are especially stable. Here such powerful compressive stresses are formed that even a supercritical crack is often unable to overcome them.

In 1934 the Soviet physicists N. A. Brilliantov and I. V. Obreimov detected areas in NaCl crystals in which the crystalline lattice was sharply turned about. They called these crystals irrational twin crystals. This term evoked heated discussion because it was ascertained that these defects had nothing in common with twinning. V. L. Indenbom and A. A. Urusovskaya of the USSR proved that the Brilliantov-Obreimov twins are associated with plastic deformation. Dislocation processes lie at the root of this defect. It was ascertained that due to non-uniform stress, the cross section of the crystal was not deformed uniformly. As a result of numerous slips, adjacent areas of the crystal turned to each other at angles of several degrees. The resulting dislocation structure is similar to that formed in the case of simultaneous slippage along different intersecting slip planes. Experiments and calculations have shown that around and within the Brilliantov-Obreimov bands there are very powerful fields of compressive stresses. We already know that this gives hope that the defect will have a hindering effect. It is also of interest that such a band tends to hinder a crack not only from the front but (in case of a breakthrough) from behind it as well: something like what ancient Greek warriors did when they lay down on the ground and covered themselves with their shields, allowing the enemy to pass, and then attacked from the rear. The physical meaning of this phenomenon is understandable. The Brilliantov-Obreimov band creates compressive stresses both in front and behind itself. It is no wonder, therefore, that these bands are unparalleled in their effect on a crack. If one of them retains a fast crack for 20-30 μs, two or three of them stop a crack no matter at what rate it propagates.

When speaking of defects capable of stopping fracture we must mention the so-called fault. This is a geological term that signifies the displacement of one part of the earth's surface with respect to another, the displacement being aligned along the dip and along the strike of the fractured strata, i.e., along the surface. Physicists concerned with metals and crystals took over this term and gave it the following meaning: the slip planes of a crystal must be converted to a gently sloping step.

How is this effected? Very simply. Let dislocations of one sign pile up on one half of a slip plane to cause the plane to bend with the convex surface towards the 'protruding' extra planes. Then let dislocations of the opposite sign pile up on the second half of the

slip plane. Evidently the resulting curve will be opposite the other one. Thus, two small fault shelves are formed. It remains to join them by an inclined plane free of dislocations and the fault is ready. Faults in zinc crystals are millimeters in size. In ordinary steel they are much smaller — tens and hundreds of microns. The turning angle of the material in fault bands can be considerable — up to 30-40°. The density of dislocations in a fault is very great — up to 10 billion per cm^2.

How does such an S-shaped fault interact with a crack? Hostilely. While still at distant approaches to the crack it already retards the crack, 'advancing' compression fields against the latter. These fields act in the core of the fault also. Because they are so complicated, a crack that penetrates into the core of a fault moves in steps and disintegrates into tiny cracks. It often stops in order to create secondary 'daughter' cracks in front of itself. Then on uniting with them, it rushes ahead, and so forth. In short this is not a deployed procession, but hard work that demands large reserves of elastic energy as well as time. Thus a fault is a serious hindrance in the path of cracks — both slow and fast ones.

The time has come to sum up. What effect on fracture is common to individual dislocations, slip bands, intergrain joints, the Brilliantov-Obreimov bands and a fault? It is not a matter of isolated, sometimes, perhaps, accidental facts, events, and test results. It is important to answer the question: what is the root of the matter? The root of the matter is a dislocation and its elastic field. Not its tensile and shear constituents but only the compression field. It is this, first of all, that fights a crack. Not a small role is played by the screw dislocation line itself.

Hence, the first soldiers that stand in the path of a crack and that are capable of resisting it are the defects of a crystal lattice. That is why metal with a high resistance to fracture must contain a definite set of these defects arranged in a specific manner.

The reader can ask a question with a catch to it: what about whiskers, the bearers of maximum strength? What about monolithic monocrystals entirely free of dislocations?

I am afraid the answer is not in their favor. Dislocations and incipient cracks are formed in such materials with difficulty. But as concerns the growth of a crack that already exists in them — it will propagate very easily and rapidly. Once fracture has started in a dislocation-free monocrystal, it will proceed as if in a very brittle

body. This is not at all surprising because a shock absorber such as plastic deformation is absent. Indeed, when searching for high resistance to a growing crack we have to become like the Soviet satirist F. Krivin's fabulous character *Toadstool* (named after the poisonous mushroom):

"Everyone looks for a better place, but Toadstool looks for a worse one. Give him salty water, give him the coldest water or even hot water; everything suits him.

For everybody looks for a better place and when everybody looks for a better place then the place that is better becomes the worst of all. In order to find a better place one must look for a worse place — he understands that, the wise and experienced Toadstool."

That is why when devising means of high resistance that could oppose an existing and growing crack we cannot count on conventional dislocation-free materials with a strength close to the one that can theoretically be obtained. That would only solve one particular, though very important, problem — to repress the birth of incipient microcracks. But if a crack has somehow already appeared, theoretical superstrength will be of little avail in the battle against it. The stress concentration at the tip of such a crack, in the absence of plastic deformation, easily attains the values of theoretical strength. Therefore such a crack will propagate readily. To cope with it the crystal must possess altogether different qualities, in particular, defects must be present in it. In this incompatible contradiction between superiority and inferiority in a perfect crystal on the one hand and its simultaneous imperfection on the other hand lies one of the problems of modern metal and alloy design.

CREATION THROUGH DESTRUCTION

And he challenged all — the very heavens,
But destruction is the craving for creation
And destroying, he craved a miracle —
The Divine Harmony of Creation.

(After I. Bunin)

We have already spoken of how to deal with fracture that has to

be stopped. First of all it has to be detected with sensitive instruments that make use of the 'noiseness' of a crack; for example, acoustic transducers that respond to its 'singing' in the range of audibility of electric or magnetic devices designed for determining the electromagnetic radiation of fracture, and many others. The signals obtained are processed by computers which give the command for the explosion of microcharges. The resulting elastic waves fall on the mouth of the crack and retard it or turn it aside. This is an ideal picture but, unfortunately, it has at least one serious shortcoming. The fact is that it is possible to detect the appearance of a crack, even in the early stages of fracture, but it is not at all a simple thing to determine exactly where it is and where it is going.

This problem greatly resembles that of intercepting a modern supersonic airplane. Remote radars locate it rather far from the target; they then communicate with radars positioned in the immediate vicinity of the target under protection, which in their turn direct interceptor-fighters or anti-aircraft defence rockets against the enemy planes.

Only in the case of a crack everything is much more complicated. This is why an enemy plane can be located at a distance of thousands of kilometers from the target. Therefore the air defence has at least ten minutes to prepare for resistance. In the case of a crack the entire time of fracture can constitute hundredths and thousandths of a second, if not less. And in such infinitesimal periods of time it is necessary not only to locate the crack but to determine the direction and speed of its motion. If this is not ascertained, the impact of elastic waves will be altogether useless or fall on places that the crack has already passed and completely destroyed; whereas it must hit the crack right in the 'jaw', right in its tip. In this game with a swiftly moving crack the stakes are very high and the difficulties are exceptionally great, because a crack can originate in any crystalline grain instantaneously and because the time is inconceivably short.

The time is so short that at present there are as yet no computers capable of processing the signals from the transducers that keep track of a crack. Therefore it is still virtually impossible to calculate the exact location of a fast crack. Besides, everything is made more complicated by the fact that the crack sometimes grows by fits and starts and quickly alters its direction. That is why it is impossible to

predict anything. The flight of a plane is more 'leisurely' and smoother.

Things are better in the case of a fatigue crack. It grows slowly, 'sensibly', in jumps that follow one another. Its trajectory does not alter. That is why American physicists applied the simplest methods of triangulation to cracks growing in a nuclear reactor. They made use of an acoustic echo for this purpose. The exact site of fatigue fracture was found by means of three differently positioned transducers that simultaneously determined the sounds emitted by the crack. It is interesting to note that the investigations were carried out remotely, the measuring instruments being at a great distance from the reactor itself (up to 90 m).

It is clear that automatic methods of hindering cracks can be most realistically applied to fatigue fracture. In this case the vast possibilities of modern computers can be fully utilized — there is plenty of time, as the process proceeds quite slowly.

But fatigue is only one kind of fracture. And if in the future we will be able to cope with it, there still remains a very great number of cases when a destructive crack is impetuous.

What should we do in such cases? How can we locate the crack? And, in general, must we necessarily locate it? Are there no ways to avoid doing this?

It appears that in some of the simplest cases there are such ways. Suppose we know, at least approximately, the direction along which a crack may go. Then, at right angles to this direction, along the entire structure we set up something like a fence — we string a thin insulated wire across the metal, gluing it. The growing crack ruptures this wire simultaneously with the metal structure. And if a weak current was previously passed along this transducer, it is possible to receive a signal indicating the position of the crack at any given moment. But this method is not always suitable because it gives only one coordinate of the crack and it is very difficult to glue the wire to the metal in such a way that they are both ruptured at exactly the same time. Usually the wire lags behind and is ruptured after the crack has passed and long after its tip has moved ahead and its faces have moved apart.

It turns out that the location of fracture is the hardest problem of all: it must either be solved at once or be dispensed with altogether. Recalling the student saying that a smart person 'will not climb a mountain but try to go around it' let us try to find a side path too. Let us begin from afar.

The girders of a large bridge are periodically examined and a crack is discovered in one of the steel beams.

What should the repairs team do first of all? A hole is drilled in the mouth of the crack. What for? In order to reduce the stress concentration and to stop fracture. Afterwards this crack is carefully welded and a steel 'patch' is applied onto the damaged section.

So what? To fight a crack a simple drill can be used to bore a hole at the tip of a supercritical crack?

But it is clear to any sensible person that it is impossible to find such a craftsman who could do this in one or two microseconds. Besides, in these microseconds the crack does not stand in one place but contrives to cover a path from several millimeters to a centimeter long. It is also clear that the crack cannot be beheaded or even 'have its hair clipped' by any conventional mechanical means.

Just the same this is possible, but by altogether different means. Let us suppose that we have at our disposal a method with the aid of which we can heat the mouth of the crack. In this case the material in the vicinity of the tip must expand. But the surrounding matrix of the metal will hinder this. In other words, the site where interatomic bonds are broken will be compressed to a greater degree, the higher its temperature and the greater the difference in

temperature between it and the surrounding area. It is clear in what way the resulting thermal stresses will affect fracture: they will considerably hinder it.

But even more can be achieved by us. Suppose we continue to heat the metal until near the tip of the crack it reaches the melting point. Liquid metal will flow out and a hole will be formed at the mouth. The crack, on running into it will be stopped, first of all because the stresses along the contour of the hole will be hundreds of times less than those on the crack and secondly, its surface is red hot and is consequently compressed by the surrounding cold metal.

But how is this actually accomplished? For instance, what if we have to save from impending disaster a large sheet of metal under tension due to any arbitrary force? We can place a good-sized bank of capacitors not far from it. A considerable electric charge is stored in it. Let us connect the bank to the metal being protected by means of a high-speed switch.

Another element of the emergency system is a receptor — a transducer — attentively 'listening' to whether a crack will appear. It can be any kind, in particular, an acoustic transducer. It must, however, be deaf to all sounds except those emitted by cracks. We can help it to do so. As a rule any accidental excitation has a low-frequency audible spectrum. A crack is another matter. It 'works' in the inaudible ultrasonic range. Therefore the transducer must be taught to react only to ultrasounds and not to pay any attention to anything else.

But that is only one of the principles of the transducer. Another one, no less important, can be expressed by the Latin saying: *'Semper paratus'*, which means 'always ready'. The transducer must always be 'ready for action' like radars that control interceptor planes and air-defence rockets. The metal 'bears its cross' and tranquilly serves, because the transducer is on the watch during the whole time that the structure works — day and night, in cold weather and in hot weather.

Now a crack has appeared and has begun to propagate in the metal. This is just what the ever vigilant receptor was waiting for. It heard the crack at once and transmitted a signal to the switch which cuts off the electric charge of the capacitors from the structure. The switch immediately opens and a flow of electric energy in the form of a short powerful electric impulse gushes into the metal sheet being protected.

And here the remarkable properties of a high-frequency current are manifested. It tends to concentrate in the thin surface layer of the metal. This phenomenon is called the skin effect. It is not necessary to inform this impulse where the crack is located — it instantaneously detects the crack by itself. Neither does it need to know the speed of fracture — it is negligible in comparison with the propagation speed of electromagnetic signals or light. It is as if a wide search network were cast on the structure. It instantaneously concentrates almost all the energy of the discharging capacitor on the crack. The point is, first of all, that a crack is a surface. But it is of no less importance that the crack cleaves the open area of the metal along which the high-frequency current flows. It flows around the crack, at first along one of its faces, then dives into the sharp tip, then runs along the other face. What happens at the tip is most interesting of all. The radius of fast fracture is infinitesimal and the current density reaches enormous magnitudes which are greater, the more brittle and dangerous the fracture. The enormous current emits a titanic quantity of Joule heat into the tiny space of the mouth of the crack. In a few microseconds the metal is heated, melts and evaporates. From the tip of the crack there literally gushes forth a fountain of matter — from particles and droplets of metal to plasma; the previously very sharp tip is converted into an opening that is fractions of a millimeter or even millimeters in size, with fused edges. Just like in the Persian saying: "Show us an opening and we will make a gate out of it." This gate is an insurmoun-

table barrier in the path of a crack. The latter cannot break through it. In this way fracture is hopelessly defeated by ruthless havoc which, strange as it may seem, is a boon for the metal structure.

This method is favorably distinguished from other means of hindering cracks by the fact that metal with the halted crack can still serve for a long time. The reason for this is that the resulting opening completely paralyzes any attempts of the crack to grow. This is all the more positive because it is not difficult to 'drill' as large a hole as we like.

And the fountain of life springs
from destruction . . .

(After Johann Wolfgang von Goethe)

Chapter 4
Fracture – a Friend

A SHARP KNIFE

There's a whole world here, alive, varied . . .

(After F. Tyutchev)

No matter what bad things take place on the Earth, in this chapter we will speak only of good things that occur. That is why we will look at a crack through rose-colored spectacles. It will then appear that cracks are often useful.

On the surface and deep inside our planet there are a great number of gigantic cracks and crack-like ravines. Often they are made use of in the national economy, for instance, when planning canals, or in selecting a site for open-pit mining.

Mountain climbers know how important small cracks are for scaling smooth cliffs — they are something with which to gain a foothold. They are also utilized by plants that grow in bleak mountainous places, on very steep slopes.

And what about fracture? In our everyday life we encounter its beneficial effect at every step.

Let us consider such a laborious process as tilling land for raising crops. The plow cutting the soil, the spade piercing it, the mattock, the hoe — are all tools that create through destruction.

And what about the excavators 'shovelling' the surface of our planet? And the numerous mining cutter-loaders gnawing it, and borers many kilometers long drilling oil wells?

All are cases of fracture . . . but useful fracture that brings us well-being and good in the widest sense of the word.

This lies on the surface. But on the gigantic stage of our planet, how many small, inconspicuous but interesting roles are played by fracture. It appears, for instance, that we can cultivate mushrooms in our own orchard. For this purpose it is sufficient to make a number of cuts with an ax in the stump of an old tree . . .

Let us recall the work of a glass-cutter. First he makes a shallow cut in the glass with a diamond. Then by tapping it under the cut he produces a crack in it. Placing the glass on a table so that the cut precisely corresponds to the edge of the table, he exerts pressure on

the protruding part. On doing this the crack propagates along the stress concentrator, dividing the sheet of glass into two parts. In glass-blowing plants the glass vessels are separated from the blowpipes in another way. The well-known Soviet glass specialist N. Kachalov wrote in his book *Glass* — "... the vessel is separated, or as glass makers say, is 'knocked off' by means of applying a wet iron band to the appropriate place. Due to abrupt local cooling an encircling crack appears in the glass. On tapping it lightly the shaped vessel separates from the blowpipe".

In experiments physicists use a soldering iron for this purpose. The glass is heated right in front of the cut. The material at the place that is heated expands and splits the glass along the cut. Then the soldering iron is conducted in front of the crack, producing a tensile stress at its tip. The direction in which the crack moves can be controlled at our will.

Pay attention to the fact that whatever method is used for severing glass, it is always a crack that is employed as the cutting tool. A crack is also used in this capacity when cutting precious stones.

Writing about industrial espionage, J. Bersier notes that since prehistoric times people have tried to find out industrial secrets, in particular, the secret of cutting and polishing precious stones. This is a very complicated technique which modern researchers, with

great difficulty, have only partly rediscovered. No less complicated, for example, is the method of splitting with one blow a square plate of flint into four parts in order to isolate the nodule in it. This demands high skill. Spies hunted for such secrets and probably stole them more than once in the course of the past 10 or 20 thousand years.

Every crystallographer and crystal physicist knows that it is not a simple thing to cleave a crystal. However, in almost every investigation of a crystal splitting is preferred to cutting. This is simpler and more convenient. But the point goes beyond that. When we cut a crystal we greatly distort its surface and impregnate it with impurities. After that it is unfit for investigation. Splitting is another matter. If it is performed skillfully, the rapidly moving crack hardly changes the surface of the cleavage and becomes an excellent sterile object for investigation, to say nothing of the fact that the surface of the fracture often interests us as a witness of the processes occurring during fracture. It is not accidental, therefore, that a well-known American physicist begins one of his most serious papers with instructions on how to split crystals. He writes that many crystals were spoiled in the attempt to obtain a cleavage; however, after experiments were carried out on several thousand crystals, some skill was acquired. He also notes that this does not eliminate the element of art in cleaving crystals, but it renders substantial aid.

A RELIABLE FLAWLESS BLADE

Honored be science for making plain
What we ourselves cannot explain.

(After M. Svetlov)

Someone once said that a sharp tongue is the only tool that does not become dull from constant use. I want to question the truth of this statement and point out another instrument of this kind — a crack. Imagine that at a machine shop there arose the necessity of cutting metal having a large cross section (say, half a meter in diameter). Of course, this can be done in many ways, for example, on a metal-cutting machine tool or a saw. This, however, consumes

much time and energy and a part of the metal (not a small one) is converted to chips. In this case it is feasible to make use of a crack. First of all, it is not afraid of high-strength steels and alloys. On the contrary, the stronger the material, the more sensitive it is to stress concentration and the more easily it is cut by a crack. In the second place, no cutting tool will accomplish the task faster than a crack which is as quick as lightning. In the third place, the energy consumption of a brittle fracture is negligible. In the fourth place, for all its lack of mercy, a crack does not devour the metal, does not convert it to chips. A crack has still another advantage over tools: it does not have to be sharpened. The tip of a fast supercritical crack does not become blunt in the process of fracture. On the contrary:

Steel may corrode,
A heart may break,
But on meeting resistance in its path
A cutter only the sharper becomes . . .

(After Ya. Belinsky)

All this is very tempting but not at all simple. It is well-known that in science all that lay on the surface was picked up long ago. It is not simply a question of 'taming' fracture, but rather of becoming friends with the crack, of intentionally using its destructive pro-

perties for the good of mankind. However, we must not forget how bad-tempered, how unscrupulous a crack is, that the God it worships is stress, that it can instantaneously change its direction; we must not forget these nor many other traits of a crack that are not very attractive. In short, a crack is not a reliable friend and we must always be on the look-out with it.

We realize this. Yet what is required of a crack prior to attempting to use it for cutting metal in machine building and metallurgy? First of all it is necessary that fracture set in as soon as possible so that plastic deformation which precedes it is as small as possible. This is important for achieving low energy consumption in the process of cutting and for preserving the shape of the metal being cut. Besides, the crack must be 'governable'; it must propagate strictly along a preset path.

Otherwise the game is not worth the candle. If the crack deviates from this path, only approximately keeping to the required direction, in order to obtain a good surface it will be necessary to machine the part later. This should be avoided.

The first question confronting us is: how quickly or how slowly should the crack grow? If it grows too slowly the process will be inefficient and, what is of even greater importance, plastic deformation and, consequently, the energy consumed in fracture will be too great. Therefore, a fast (but not too fast) crack is preferred. It appears that at moderate speeds (of the order of 1 000 m/s) the surface of the cut is sufficiently smooth. At speeds greater than 1 500 m/s, however, the crack begins to jump convulsively from side to side. Large curved ridges and a complex system of steps appear in the cut. Besides, some parts of the fractured surface are turned through an angle of up to 10-12° with respect to one another. Upon further increasing the speed things become still more complicated and at 1 800 m/s branching sets in. A fractured surface that is full of flaws, is uneven and, in addition, in which the crack has branched, is not suitable for machine building.

Therefore, it is not hard to define the conditions required for the propagation of a crack in the cold fracture of metals. On the one hand, the speed of the crack must be as great as possible in order to lower the energy consumption of fracture. At the same time it should not be so great that ridges appear on the fractured surface. Speeds in the range of 1 000-1 500 m/s are preferred. Here the energy consumption is low and the crack is still sufficient-

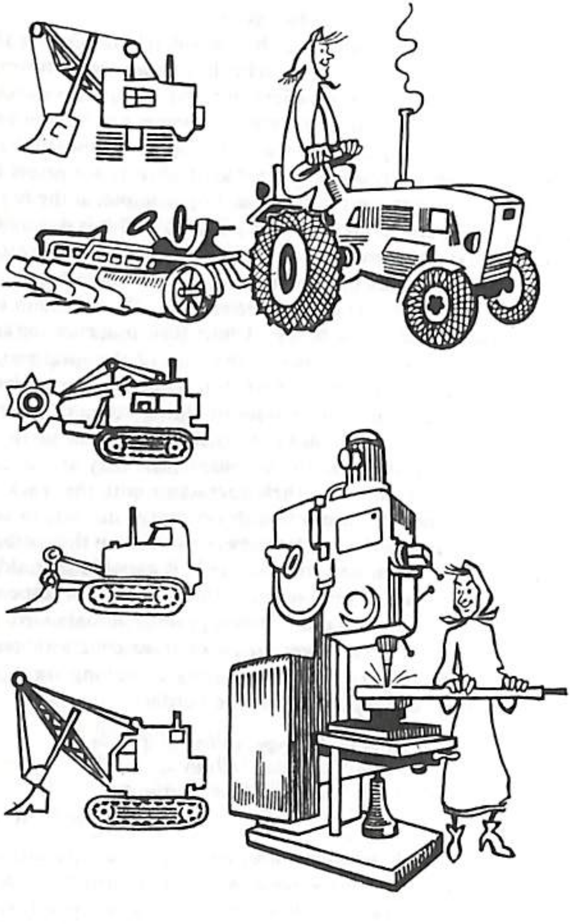
ly stable. This is the first demand a crack must meet, so that "the fountain of life springs from destruction."

But this is only the beginning. It is absolutely imperative that the crack be stable, i.e., that its path be the one we need. However, this is not simple — fractures are sensitive, in particular to waves of various nature. It is good if these elastic waves are intentionally 'organized' by us to regulate the crack. It is quite another matter if they appear accidentally and are capable of altering the preset trajectory of the propagation of the crack. For example, at the border of a specimen the crack often behaves unusually. This is due mainly to a change in the stressed state which takes place for two reasons. First of all, at the border of the specimen there is no component of elastic stress perpendicular to the free surface. There remain only tensile stresses parallel to the border. Under their influence the crack tends to propagate at right angles to the edge of the specimen, no matter at what angle it moved at first. But another process hinders this. During fracture numerous groups of elastic waves of different kinds move along the metal and their incidence on the surface of the specimen can be at any angle. Consequently, they are reflected at arbitrary angles. That is why their interaction with the crack is so varied that it cannot be foreseen with certainty. In fact, in sufficiently brittle materials the crack rarely comes out on the surface at right angles to it. Often near the border it is capable of suddenly pirouetting, not once, but several times. This is especially characteristic of fast cracks that have become unbalanced and, therefore, are very sensitive to various, even transient elastic pulses. Such cracks originating, for example, during branching are capable of turning sharply as they approach the border.

. . . It flares up like rage, coiling as it rages
But, like a coil, on going halfway up
It springs, expanding in its rapid growth . . .

(After R.-M. Rilke)

Sometimes a crack grows without coming out at the surface of the body. But when the stress reaches a certain critical value, the crack instantaneously turns around and emerges on the surface. Its behavior is so unrestrained and vigorous at the surface that special measures have to be taken. Their essence is: in case use is not intentionally made of reflected waves, everything should be done to counteract their influence on the growth of the crack. Otherwise there can be no hope that the crack will propagate steadily. And in-



stead of a smoothly fractured surface, we will get a curved one with any number of 'hills' (raised parts).

What else can hinder a crack from doing whatever it pleases? First of all, the internal residual stresses, especially if they vary from point to point. In up-to-date rolling, they are not very dangerous. More complex is the motion of a crack in steel from grain to grain, producing a surface roughness of the fracture. The crack is also sensitive to the structural constituents of steel. This is redeemed by the fact that with an increase in speed, the crack becomes omniverous, and at a speed of 1 000 m/s it grows successfully in ferrite and pearlite. At such speeds the crack becomes brittle and cuts any one of the constituents of steel.

The surface of the fracture is impaired by dislocations, intergranular boundaries and other flaws in the steel. However, nothing can be done about that — these are natural limitations of the method. It can be considered that the smallest surface irregularities of rolled steel cannot be smaller in size than a grain in steel.

It is very important to conduct cold fracture of metals in such a way that considerable plastic deformation is not produced in it. This is important not only in order to break the metal easily, without great energy consumption; deformation must by no means be allowed to change the structure of the steel. However, there is always the danger that this will occur if there is considerable deformation. This might result in the appearance of networks of many micro- and macrocracks.

And if there are many cracks, fracture either proceeds simultaneously from many centers or it is complicated by the interaction of the main crack with the other cracks. In both cases the fracture surface is damaged. To avoid this, the main crack is 'shaped' intentionally: a stress concentrator is previously applied to the rolled steel. The stress concentrator makes the crack originate where it is necessary and facilitates its growth to the critical length. In such a case the other cracks are doomed beforehand. They will surely 'lose', while the main crack will 'win'.

We already know that a crack is unsteady. There are plenty of reasons for this: the effect of the structure of steel, the stress fields, branching, the various wave processes and many other factors.

That is why if we want to make use of a crack as a tool that we can depend on we must create conditions that will impede the effect

of such factors. This by no means excludes all the above-mentioned reasons, often accidental, that cause unsteady fracture. It merely means that it is absolutely necessary to create conditions needed for the steady growth of macrocracks; there are two ways of doing this. The first is to superimpose an externally induced macrofield over the accidental elastic fields, which, roughly speaking, will suppress them and assure a uniformly stressed state in the entire area of crack propagation.

The second way is finer. In this case it is not necessary to superimpose a field over the entire metal being fractured, which is far from always convenient. Why deform the entire area when the crack will move along a small part of it? Would it not be better, in this case, to create a narrow deformed corridor, like a waveguide, to assure that the crack propagates in the required direction along a definite path? Such a method demands less energy and the result would be the same. What basic ideas are there for making the uncontrollable crack, the 'brigand', follow the course of a disciplined toiler that can be controlled?

There is, in fact, only one idea. It has recently been proposed by scientists and consists in the following. Let us apply compressive stresses along the direction of a propagating crack. Inasmuch as the crack grows due to tensile stresses that are perpendicular to its faces, the compressive stresses do not prevent it from moving in the required direction. But if all of a sudden the crack 'decided' to show its bad temper and turned aside? It is here that the compressive stresses show what they are good for. On turning, the crack exposes its flanks and the stresses 'swallow' it — thus, the crack cannot move in any direction except the main one. Something like a road sign that prohibits a turn. In contrast to a sign, however, the compressive stresses are actually a physical obstacle. Under such conditions the crack is forced to submit to discipline. It is only necessary that the applied compressive field should, without fail, exceed any of the other elastic fields capable of inciting the crack to commit 'outrages'.

The time has now come to tell the readers how cracks are used to cut rolled products into billets of given lengths which are used to manufacture parts in machine shops.

Let us apply the above-mentioned idea to various cases of cutting metal. Let us assume that we want to break steel by bending. If we fail to take special measures the crack which starts from

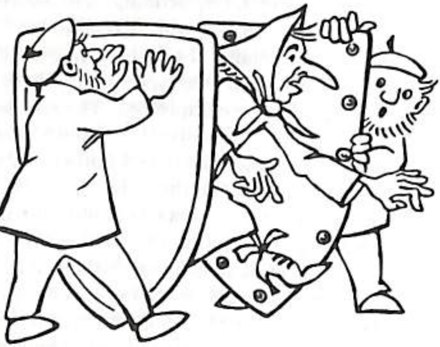
a cut on the expanded side of the specimen will move to the compressed part. Here complications will arise. The crack will begin to change its direction, i.e., try to deviate from the main one. And not only in steel! Break a small wooden stick or pencil. In the expanded area the crack will propagate normally, but at the end, in the compressed area, the wood will split in the direction parallel to its axis. Nothing will be left of the monolithic crack due to the compressive stresses that inevitably originate on bending a rod. In order to suppress them, let us compress the outer surface of the rod. For this purpose we will use mechanical compression. It plays a dual role. First of all, the compressive stresses that arise in the entire cross section of the specimen will put under 'taboo' any 'tricks' of the crack and compel it to go exactly along the prescribed route. Secondly, still another favorable trait of such a stressed state is manifested. Imagine that you have some plasticine in your fist. On squeezing it, it will be squashed out from the ends of the fist. Steel will not flow from a fist. But the tensile stresses that arise in it when steel is compressed externally tend to rupture the specimen along its axis. The stresses are relatively small, but none the less, they assist fracture and push the crack ahead. Thanks to the two-fold favorable effect of external compression on the metal specimen, it can be broken by ordinary bending and the resulting fracture has an excellent surface with only slight roughness. This has become possible due to the victory over the crack.

How can such stabilizing compression be accomplished in practice? This can be done mechanically. But there are other ways. For example, prior to breaking metal by bending, it is cooled for a short time in liquid nitrogen. Its surface will then contract. The core of the metal, however, that retains the initial temperature, hinders this. As a result the surface of the specimen will be expanded, whereas the inner layers will be compressed. The tensile stresses on the outside are very convenient because they promote the formation of an initial crack. At the same time the compressive stresses inside the body of the specimen fulfill the role of a watchman who steadies the crack. In the end the crack is readily formed and propagates steadily, leaving behind it an excellent fractured surface.

A very effective method of fracturing metal is hydrostatic compression. Here the principle is the same, but it is accomplished differently. The medium that provides and imparts the pressure is a liquid — water or oil. A special compressor compresses it to a

relatively high pressure equal to tens of thousands of atmospheres. As a result the metal finds itself in a hydraulic 'fist'. There arise stresses that stabilize the crack and fracture the specimen. The latter are directed exactly along the axis. Therefore, the fractured surface is ideal: when plexiglass is fractured, it is mirror-like; in the case of metal its roughness does not exceed steel grains in size. A specific feature of this method is that the initial crack is very easily generated. For this purpose it is sufficient to make an infinitesimal cut on the surface of the metal specimen. The pressurized liquid penetrates into the tiniest pores and produces additional cleavage that promotes the appearance of a crack. (The two methods described above have been worked out by Soviet researchers G. A. Baryshev and G. B. Rodyukov under the guidance of the author.)

Hydrostatic fracture is a very promising method, but . . . as a Japanese proverb says, "he who does not know what he wants must at least know what is wanted of him by others." We want to work out effective methods of cutting metals. So do others. However, these methods must not only be effective, they must be simpler than the customary ways of cutting. In this connection it is necessary to point out a very weak spot in hydrostatic compression — the need to provide reliable packing between the vessel containing the highly pressurized liquid and the surface of the specimen. But this specimen is a rolled product with a very uneven surface that, moreover, varies from one part to another. Unfortunately, at the present time this is an incredibly complex problem to solve, that detracts from the merits of this method.



To do away with packing and still attain the high pressure that is needed for fracturing it is convenient to make use of pulse hydrostatic compression. The idea consists in the following: the speed with which pressure is delivered to the site of breaking is much greater than the speed with which it falls due to leakage. For this purpose, for instance, it is very convenient to use an explosive wire that encircles the specimen. Both the specimen and the conductor are contained in a tank with water. By means of a powerful electrical pulse, the conductor explodes and surrounds the specimen with a compression field under a pressure of approximately 100 MPa. This is sufficient to fracture plexiglass but, unfortunately, not metal.

A more exotic method of fracturing metal is by compressing it with a powerful magnetic field which is created by a single-coil solenoid having a field that reaches 700 kE. The resulting tensile stress in the metal is 0.8 GPa. This method does not require any packing. Moreover, by increasing the energy of the capacitors it can be used, in principle, to fracture any metal.

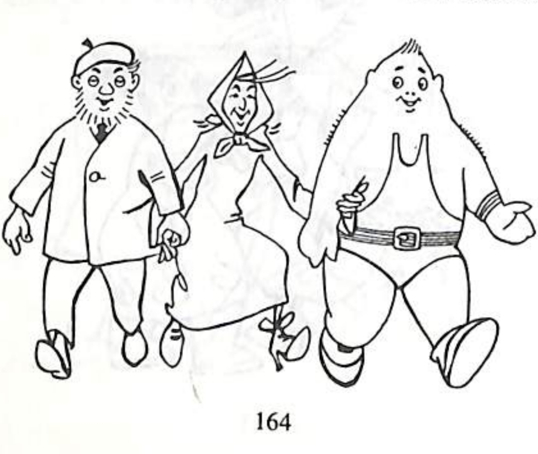
But (as you see, here also a 'but' cannot be avoided) this method is not suitable for mass production because of the danger incurred and technological troubles which arise from working at high voltages. Most likely, this method is for the future.

To summarize, both methods appear to be very promising and reliable for stabilizing the fracture of metal. It is true, however,

that they are suitable only for rolled products of comparatively simple shapes, provided the crack propagates rectilinearly.

Perhaps the reader is familiar with how the firing of tanks was conducted in World War II — not with shells but with solid metal bars. In this case the tank was fired in an unusual way. The bar did not break through the armor but tore out metal from the inner surface, flinging it inside the tank. The mechanism of the process was as follows. When the bar hit the armor it created a compression wave in the latter. The wave then propagated to the second (inner) surface and on being reflected from it was converted into an expanding wave. Roughly speaking, the wave was repelled from the surface, driving it inside the cabin. That was how the metal was torn away, wounding or killing the crew. The Soviet researchers, Yu. I. Golovin, V. M. Umrikhin, G. B. Rodyukov and the author, decided to make use of this principle of cleavage for cutting metal.

For this purpose stress concentrators (consisting of cuts made with an ordinary chisel) were incised on a steel bar several meters long. Then a short longitudinal knock was applied to the butt end of the rolled bar. This can be done in many ways. For instance, we can fire the steel blockhead of a hammer with a flying speed of 70-100 m/s; we can accelerate the head by means of a magnetic field. Other ways are possible. It does not matter in what way we create a compressive wave. It is essential that such a wave, as a rule, rapidly becomes flat. This means that its front along the entire profile of the rolled bar is at right angles to its surface. Therefore, the



crack that appears on the surface of the metal propagates in a direction precisely perpendicular to the length of the bar and the resulting fractured surface is excellent. Furthermore, the expanding wave moving through the specimen cuts the metal along each concentrator. As a result, with one blow, a bar many meters long is divided into tens of blanks.

THE END

Not death in the dark of night —
Rather, birth at daybreak!
(After Ch. Baudelaire)

The book is coming to an end and it is of great importance whether on finishing it our mood will be inconsolable gloom cast by the dismal pictures of destruction or an optimistic outlook on the world surrounding us since we have become acquainted with fracture and now know that it can be controlled.

It is enough to look around us to see that thousands of various devices, machines and mechanisms faithfully serve man, facilitating his labor. High strength and durability, is the natural, usual state in engineering. And if this is so, we have solid grounds for a good mood.

As far as fracture is concerned, it certainly exists. But we resist it everywhere. Prophylactic measures for the prevention of fracture are already taken at the time of designing and constructing. Their purpose is not to allow the formation of even a small crack. There is such a concept as the safety factor. It indicates how many times the ability of a structure to withstand external loading exceeds the loading it is actually subjected to. Sometimes we hear: the reserves do not 'drag on the pocket'. In this case that is not true. Unused reserve strength is the ballast that consumes scarce metal. Nevertheless, in any structure there are always such reserves, as a safeguard against possible failure.

But let us suppose that the reserves of strength are exhausted because of some unforeseen circumstances, and a crack does appear in the metal. That, of course, is bad but far from hopeless. We

are now convinced that the appearance of a crack does not necessarily imply the end of a structure. It is by no mere chance that the optimist Goethe wrote:

. . . The end? What an absurd word!
The end of what? Just what has happened? . . .

At the present time we already have at our disposal tens of different ways of stopping fracture, thus assuring structural strength and avoiding accidents. I believe that the time is not far distant when we will not only be able to prevent and stop fracture ourselves, we will also be able to teach metal to cure itself. Such self-healing will bar accidents and catastrophes from the life of mankind forever.

TO THE READER

Mir Publishers welcome your comments on the contents, translation, and design of the book. We would also be pleased to receive any suggestions you care to make about our future publications.

Our address is:
USSR, 129820,
Moscow, I-110, GSP,
Pervy Rizhsky Pereulok, 2,
Mir Publishers

Printed in the Union of Soviet Socialist Republics

A BOOK FOR YOUR LIBRARY

ON RARE AND SCATTERED METALS. TALES ABOUT METALS

S. Venetsky

As the title suggests, this popular-science book deals with the history of discoveries, the properties and uses of the most important rare and scattered metals. In it the reader will find fascinating information about treasure-troves being formed in our day, about a black notebook which witnessed a great scientific discovery, about an element which has vanished from the face of the Earth like the once omnipotent dinosaur, about the role of some metals in criminalistics. The author hopes this book will be enjoyed by lay readers and specialists alike, by all who are interested in the history of metallurgy, chemistry, and the science of materials.

V. Finkel

The Portrait of a Crack

Fracture. . . We encounter it every day, every hour. Here a feeble blade of grass, so green and undaunted, has victoriously shot through the asphalt pavement. How could this happen? There a mighty metal structure that was expected to stand for ages suddenly broke. . . Why? What causes disaster and fracture in a world of the strongest materials? How does a microcrack behave? From whence its strength and treachery? How is man learning to control this terrible force and to turn it to his own advantage? The author answers these questions and many others. The easy, natural manner of narration and the poetic quotations illustrating the author's conceptions make the book interesting as well as instructive.

The book is intended for the general public, for all those who want to understand one of Nature's greatest mysteries. But it is primarily addressed to young people faced with the problem of choosing a profession.

Mir Publishers Moscow